PHOTOMETRIC DYE STUDIES IN THE MAGELA CREEK SYSTEM
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by

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1. Background to the 1979 Field Experiments

1.1 Introduction

In March 1978 a team from the Centre of Resource and Environmental Studies (hereafter CRES) undertook a field study using fluorometric dye techniques in the Magela Creek System. That study was funded by the office of the Supervising Scientist and the major aims were to:

i. establish if the techniques were appropriate to dispersion studies in the area;

ii. obtain information that would be useful for hydrological and water quality modeling of the Magela Creek System especially in relation to problems associated with the discharge of waters from the Ranger uranium mine and milling plant.

The results have been presented in Smith, Young and Goldberg (1978a and b) and an outline of possible modeling strategies given in Goldberg (1978).

The techniques were selected in order to provide useful information on dispersion. One of the most valuable applications of the technique is to investigate changes of the dispersion pattern under differing hydrological conditions, of which high stage conditions are perhaps the most critical. For such work to be undertaken in a meaningful way the instrumentation and field workers would need to be resident in the local region. Thus, in late 1978 CRES agreed to undertake a second field season of which a major aim was to demonstrate the field techniques to the Water Division of the Department of Transport and Works of the Northern Territory Government.

The work described in this report was funded by the Northern Territory Government but at all stages the Supervising Scientist was
informed. A hydrologist from Ranger was also present during much of the
fieldwork and close liaison was maintained with a team from the
Australian Atomic Energy Commission (AAEC) who were undertaking field work
for Pancontinental.

Thus, the main aim was to demonstrate the technique but the
Applied Systems group in CRES will continue to investigate modeling
methods based upon the data collected.

For the 1979 season three staff members of CRES took part in
the field work, namely Dingle Smith, Tom Beer and Mark Greenaway.

1.2 Acknowledgements

We would like to thank the staff of the Water Division for their
coop-eration at all stages of the work. The assistance of C. Marlow, the
Engineering Officer directly concerned with the study, was especially
valuable and did much to assist with the success of the various experiments.

The co-operation of the Office of the Supervising Scientist, the
AAEC, Ranger and Pancontinental are also gratefully acknowledged. The
assistance of Neil Conway with the air photography was much appreciated.

We would also like to record our thanks to the other members of
CRES in assisting in many ways towards the production of this report.
2. Dye Release from the Projected Ranger Outfall

2.1 Introduction

This experiment is essentially a repeat of that undertaken in March 1978. The objectives were to compare the results of those obtained in 1978 and to:

a. further investigate differences in dispersion at a differing discharge in Magela Creek, particularly in respect of time and travel;

b. to investigate in greater detail certain aspects of the dispersion, these were:

   i. to establish if the poor mixing observed on the traverse line in Mudginberri Billabong was general to the whole billabong or resulted from the location of the chosen traverse;

   ii. to investigate the dispersion of dye in the Magela system downstream of Mudginberri Billabong with respect to both vertical and lateral effects.

c. to attempt to ascertain the rate of dye decay in the Magela System by comparing the dye concentration figures with those for tritium. This aspect of the study is reported in Section 5.

Staff of the Water Division were involved at all stages of the work in order to become familiar with the methods employed. The results obtained in March 1978 are outlined in Smith, Young and Goldberg (1978a) and presented in much greater detail in Smith, Young and Goldberg (1978b). Possible strategies for using the dye results for
hydrological modeling in the Magela Creek system are presented in Goldberg (1978).

In this current account the results obtained in February 1979 are presented and then, where appropriate, are discussed in of the March 1978 data.

2.4 Experimental Details

Fifty litres of 20% Rhodamine WT solution (10 kg of dry weight dye) were poured into the Magela Creek at the site of the projected Ranger discharge point. The injection site was identical in location to that used in March 1978 and by various experiments by the AEWC. The dye was poured into a fast flowing channel so that the time for injection for the 50 litres was approximately 15 minutes. Staff from the AEWC added 10 Curies of Tritium during the initial part of the dye injection. The time of the input was between 1005 and 1010 on 13 February. The discharge at the time of injection for gauging station 009 was approximately 11 cumecs.

During the first few hours of the experiment the dye in the Magela Creek System was visible and hand-held photographs were taken at intervals from a helicopter. The information and usefulness of these photographs will be discussed in a separate report.

2.3 Sampling Sites and Results

2.3.1 Sites 1, 2 and 3

Sampling sites in the section of the Magela Creek upstream of Mudgeerri Billabong were selected prior to the dye injection in order to ascertain the rate of flow and the dispersion across the various channels that make up this braided section of Magela Creek. These were located at Gauging Station 009 (hereafter Site 1) which is directly comparable to Site 1 in March 1978. A map showing the locations of all the sampling sites mentioned in the text is given in Figure 2.1.
Site 2 was located on the main Magela Creek approximately 100 m downstream of the left bank tributary from Corndorl Billabong.

Site 3 was situated to correspond with the stream gauging section immediately upstream of Mudginberri Billabong.

At each of these sites samples were collected from three differing channels. To some extent the choice of channel at each site is arbitrary and it should be noted that at some of the sites more than three channels occur. Further, the anastomosing nature of the Magela Creek System is such that it should not be assumed that, for example, the east channel at Site 1 directly feeds the east channel at Sites 2 or 3.

The dye concentration of the samples collected at Sites 1, 2 and 3 are presented in Figures 2.2, 2.3 and 2.4.

At Site 1 the first arrival of dye occurred in all three channels between 1310 and 1320 hours. The maximum concentrations were also coincident in time occurring at 1350 (two vials for the centre channel were broken).

At Site 2 the situation is less clear and although the first positive samples were coincident in all three channels at 1630 hours the peak values achieved showed considerable variation. The time of peak dye concentration also shows considerable variation. In part the lower dye concentrations in the western channel are due to dilution with water draining out from Coonjimba Billabong.

At Site 3 the first positive dye samples all occurred at 1730 hours. In general terms, the peak concentrations are similar in magnitude and time for the east and centre channels but considerably reduced for the west channel. This is probably due to dilution by waters draining from the Corndorl Billabong.
An automatic sampler was positioned in the centre channel at Site 3 in order to obtain information on the rate of dye decline after the period of manual sampling had ceased. The sampler was situated in the centre channel at Site 3. The results from 1830 hrs for the automatic sampler data are shown in Figure 2.5. The relatively rapid fall of dye concentration values to background levels is clearly shown, background values being achieved on the automatic sampler by about 0300 hrs, 14 February.

2.3.2 Mudginberri Billabong - Traverses 1 and 2

In March 1978 data was collected from eleven individual stations located along a traverse line adjacent to the gauging tower at the upstream end of the Billabong. The individual stations were marked on a rope that was positioned along the line of the traverse. Surface and depth samples were collected on nine separate occasions. This data was presented in detail in Figures 6 to 47 in Smith, Young and Goldberg (1978b) and it was apparent that the mixing, both laterally and vertically, was poor especially when compared to the sections upstream of the billabong.

It was suggested that the poor mixing may have been due to the location of the traverse line which was close to the upstream end of the Billabong where water from the fast flowing channel section of the Magela Creek encounters the deeper water of the billabong.

Thus for the 1979 experiment two traverse lines were established in Mudginberri Billabong. The upstream of these is described as Mudginberri Traverse 1 and was located at exactly the same position as for the 1978 experiment. A second traverse line (Traverse 2) was positioned close to the downstream end of the open Billabong. Ropes were positioned at both traverses with individual sampling stations...
marked at 10 m intervals. It should be noted that for Traverse 1 there is an extension of water beyond the most easterly of the sampling stations. This section of the traverse was not sampled in either 1978 or 1979 due to the impenetrable nature of the flooded vegetation. The remainder of Traverse 1 consists entirely of open water.

Traverse 2 is confined between well defined banks and the whole of the Magola Creek System flowing past this point is available for sampling.

Thus in the 1979 experiment samples were collected from two marked traverse lines with stations positioned at 10 m intervals. On each occasion three samples were collected at each station on the traverses. These were at the surface, at approximately mid-depth and close to the bottom. The depth samples were all collected using depth-samplers of various designs.

Fifteen separate sets of samples were collected from Mudginberri Traverse 1. A selection of these are shown in Figure 2.6 in the form of contoured cross sections. Time series plots for a selection of the stations on the traverse are shown in Figure 2.7. The corresponding diagrams for Mudginberri Traverse 2 are shown in Figures 2.8 and 2.9. It should be noted that these samples were collected at a period of rising stage and the stage recorded at Mudginberri is given on Figures 2.6 and 2.8. The changes in stage have also been incorporated into the cross sections.

Comparison of the data from the two traverses clearly show that the mixing for Traverse 1 is poor when compared to that for Traverse 2. The first arrival of the dye at the various stations for Traverse 1 shows considerable variation. There is an irregular distribution of dye concentration with depth and maximum dye values for the sampling points also differ. The differences between Traverses 1
and 2 are further illustrated in Figure 2.10 which shows the time series for the dye concentration at the surface and depth for west and east bank stations on Traverses 1 and 2.

In broad terms the dye concentrations at Traverse 2 is consistent with good mixing while that for Traverse 1 is not. Visual observations made during the sampling on Traverse 1 note that for stations 5-8, there are relatively dead water conditions. This was particularly noticeable for observations made after 0200 hours on 14 February. The problem of the poor mixing is further discussed in Appendix 1.

2.3.3 Observations between Sites 4 and 6

An automatic sampler was located at Site 4 and the general pattern of results is shown in Figure 2.11.

From Site 5 to 6 observations were of three kinds:

a. observations made on an occasional basis from sites situated close to the flagged boat route through this area of flooded paperbark and open billabong;

b. a short run of record from an automatic sampler situated at gauging station GS 023;

c. sets of samples collected from the marked stations that form the Water Division gauging traverse known as Mayamarleopard Traverse, which in this account will be referred to as Traverse 3.

A concentration-time plot of the observations at Site 5, which is located on the centre line of Island Billabong opposite the gauging tower at GS 023, is presented in Figure 2.12. Unfortunately observations corresponding to the first arrival of the dye at this site were not obtained. Site 6 was located in Hidden Billabong and the results are illustrated in Figure 2.13.
The concentration values for the samples collected at the automatic sampler site at GS 023 are presented in Figure 2.14. It should be noted that the sampler was located close to Site 5, but the samples were from shallow water close to the foot of the gauging tower and this is likely to explain differences between the absolute dye values in Figures 2.12 and 2.14.

The samples grouped under (a) and (b) were used to yield information on the speed of travel through this section of the Magela Creek System and this aspect will be discussed more fully in Section 2.4.

Traverse 3 is, in large part, along a cross section which is choked with vegetation. However, the importance of this traverse is that it enables some estimation to be made of the path of the dye across a wide section of the Magela Creek System, i.e., to investigate whether the dominant paths are controlled by areas of open water or whether the vegetation has relatively little effect. For most of the sample runs collected from this traverse, samples were also taken at depth. This was because the weed-mass appears to increase with depth and may affect dispersion in the vertical sense. Traverses 1 and 2 in Mudginberri Billabong are free of significant bottom growth of vegetation.

Before describing the results obtained from the Traverse 3 it should be noted that there is no information corresponding to the first arrival of dye. This was due to the impracticability of taking samples at these sites during the hours of darkness.

The line of Traverse 3 is shown on the location map. At the time of the experiment nine sampling stations were available. The eastern-most of these stations is designated Station 2 and the remaining stations are regularly spaced at approximately 50 m intervals.
across the whole of the traverse to station 10, at the western extremity. Five separate sampling runs were undertaken for Traverse 3 and samples were collected at surface and depth for all nine stations. The surface dye concentration values for all the stations are presented in Figure 2.15.

The salient feature is that for the earliest run, which has the highest dye concentrations, the maximum values were for Stations 5 and 7. These are the only two stations in open water and both are located where Traverse 3 intersects the billabongs. The relative magnitude of these open water dye peaks become progressively less apparent for later sample runs at Traverse 3.

Comparison of the surface and depth observations (the depth samples were taken at 1 m) indicates that for the earlier traverses there is a much greater dye concentration at the surface than at depth. However, this changes to a situation so that for the later dye observations there is no systematic variation between surface and depth samples. Figure 2.16 presents data for two of the sample runs to illustrate this statement.

The general form of the passage of the dye is of the initial dye pulse being funneled into the major open water channels, but progressively the dye distribution becomes more even across the whole of the traverse. This is true of both lateral and depth distribution of dye concentration. However, if the total quantity of dye passing an individual point within the traverse is considered the distribution will not be even. The velocity in the channels and in the surface layers is considerably faster than in the wood-choked water between the channels, and at depth at any given sampling station. Thus to consider dye, or pollution load, passing an individual point the dye concentration values should be combined with information on water velocity.
2.3.4 Traverse 4 and Site 7

Traverse 4 (sometimes called 'Kelly's Line) extends across the Magela Creek system at a location which includes not only the major river flow but also the tributary waters from the Hades area. There are fourteen individual sampling stations, with Station 1 close to the eastern margin of the Hades embayment and Station 14 to the west of the major Magela Creek system. The stations are equally spaced, approximately 100 m apart. The majority of the stations are in heavily weed-choked water. Station 7 is situated in the open water of the main flagged boat channel to Jabiluka and corresponds closely in location to Site 7.

Daily samples were collected by the A.A.E.C, from all the stations comprising Traverse 4, for tritium analysis. Sub-samples were made available for dye analysis for the period 14 February-20 February. All the samples were collected from the surface.

The dye concentration values for Site 7 are presented in Figure 2.17, the values obtained for Station 7 on Traverse 4 are also included.

All the data collected from Traverse 4 are presented in Figure 2.18 and the time series plots for a selection of the stations are given in Figure 2.19.

The salient features are that the first arrival of the dye coincides with the more open sections of the traverse, that is Stations 5-9. The maximum dye values recorded for Stations 5-10, 12 and 13, are all for the samples collected on the morning of 15 February. The dye concentration curve for all the stations is in the form of a skewed distribution with a steeply rising limb and a longer trailing limb. The sampling interval is such that detailed comment cannot be given for the time and magnitude of the peak dye concentration. The situation for Station 7, Figure 2.7 is better in this respect.
After the passage of the initial higher peak for the central stations in the traverse the dye spreads to all the stations forming the main Magela System. However, relatively high dye concentrations are also recorded for Stations 2 and 3, and dye is also detectable at Station 1. These three stations are located in the Hades embayment and the dye concentration is considered to result from the rising stage in the Magela Creek System that corresponded to the time of the dye experiment and is discussed in Section 2.5. The significance of this 'back flow' for dispersion effects of effluent discharge into the Magela Creek System is evident. A consideration of the dye and tritium results for Traverse 4 is given in Section 5.

2.3.5 Downstream of Site 7

Sampling in this lower section of the Magela Creek System is, with a minor exception, impossible by small boat. The availability of an air boat enabled three sampling traverses to be maintained. The exception is that samples can be easily collected by small boat between Site 7 and the open water which leads to the Pancontinental base at Ja Ja. Samples were collected from two sites which are designated as Sites 8 and 9 and the dye concentrations are shown in Figure 2.20 and 2.21.

Site 8 exhibits a first arrival time which agrees with the overall situation as assessed from other sites, but there are irregularities on the trailing limb of dye concentration. Site 9, located by the Ja Ja water pump, exhibits a very irregular pattern. Both these observations are consistent with the results from 1978 and it would appear that the open water near the east bank in the vicinity of Ja Ja is not on the main flow path which was followed by the dye.

Three traverses across the extensive flooded area to the north of Ja Ja were sampled. Their location is shown on Figure 2.1.
and their positions correspond to the traverses sampled in 1978.

It was not possible to mark the individual stations on the traverses with floats and the number of samples collected on each occasion shows some variation. The aim was to collect samples that were approximately equally spaced. The majority of the samples were collected from the surface but occasional samples were taken at depth. The results are shown graphically in Figures 2.22, 2.23 and 2.24; these figures correspond to Traverses 5, 6 and 7.

The results for Traverse 5 indicate that the dye front had reached this traverse by 0830 on 15 February and that the bulk of the dye was confined to the western portion of the traverse. It should be noted that Station 1 on this traverse corresponds approximately to Site 9 (at the Ja Ja Waterpump) and that this also shows a small dye concentration. By 1000 on 16 February the dye pulse in the western section of the traverse had declined, but a pulse of dye had arrived in the eastern section. The peak concentrations of the western and eastern pulses are comparable. Subsequent samples from the traverse show a gradual decline in dye concentration and the values are broadly comparable over the whole traverse. The variations between surface and depth samples are small.

Figure 2.23 illustrates the concentration values for the eight sets of samples collected from Traverse 6. The first samples were collected at 0900 on 15 February and these show no clear positive dye concentrations. However by 1700 on 15 February very weak positives are apparent for stations in the western section of the traverse and by 0930 on 16 February these values have reached their peak concentrations. As with Traverse 5 a delayed peak concentration occurs at a later time within the eastern section of the traverse. Unlike Traverse 4 the eastern peak attains much lower concentration values than that for
the west. Again there is little significant difference between the dye concentration of surface and depth samples. An automatic sampler, to the west of the centre line of Traverse 6, was operational between 1900 on 16 February and 0600 on 20 February. The results are shown in Figure 2.25.

The results for Traverse 7 are presented in Figure 2.24. The first positive dye concentrations were for the western section of the traverse at 1000 on 16 February. Subsequent sample runs show a marked dye peak for the western section of the traverse, but the delayed eastern peak which is clearly seen for Traverse 5 is very much reduced for this traverse. For this traverse locational detail is a little better than for Traverses 5 and 6 as a distinctive dead tree close to the centre of the traverse line enabled a comparison to be made with the location of samples between differing sample collections.

Figure 2.26 shows the variation of dye concentration with time for Traverses 5, 6 and 7. For Traverses 5 and 6 these concentration curves are for two stations, one close to the eastern end of the traverse and the other to the west. For Traverse 7 an additional station close to the centre line of the traverse is also included. These clearly demonstrate that pulses of differing strength arrive at differing times towards the eastern and western sections of the traverses. Further the relative magnitude of the eastern pulse progressively declines down the system. In general the dye values show little variation with depth and the dye concentrations in relatively open water are little different to those at adjacent stations with substantial weed growth. There is some indication that close to the first dye arrival there is more concentration at the open water sites.
It was not possible to establish additional traverse lines further downstream in the Magela System. However, it should be noted that the dye concentration at Traverse 7 is such that the dye concentrations, certainly under the prevailing discharge condition, could have been detected several kilometres further downstream. On 20 February a separate dye experiment, described elsewhere in this report, was undertaken in the vicinity of Jabiluka Billabong. The 'background' dye concentrations to this later experiment clearly indicate that dye from the earlier experiment was present in the area although it is not possible to make any detailed comment on times of travel or dispersion.

2.4 Time of Travel

The time of travel, and therefore the velocity, can be expressed in various ways, namely for the first arrival of the dye, for the dye peak and for the centroid of the dye concentration curve. The most useful single measure is probably the latter. The accuracy with which these various times, and therefore velocities, can be calculated clearly depends on the detail available to plot the dye concentration curve. The various curves for particular sites have been presented earlier in this section and the variability in the data can be seen. In some cases the problem is that the number of points for a particular site do not allow a precise concentration curve to be drawn, or calculated, while in other problems are caused by differing stations that go to make up a traverse line having a whole family of concentration curves. In other cases, for example Site 5 and Traverse Lines 5, 6 and 7, the curves do not follow a regular form. A possible solution to some of these problems is given in Appendix 1.

However, despite these limitations velocities that correspond to first arrival, peak concentration and the centroid of the dye mass can be given for many of the sites. The values for a selection of the sites
are presented in Table 2.1; if required estimates for other sites can be calculated from the curves presented in this report for other sites or for individual Stations on the Traverse Lines.

2.5 Comparison of the Velocity data for 1979 and 1978

The velocity figures for comparable sites from the experiments of 1978 and 1979 is given in Table 2.2. 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 821 009 (Site 1 in both 1978 and 1979) was provided by the Water Division and is illustrated in Figure 2.27. Thus the dye injection, at approximately 1015 on 13 February, was immediately ahead of a major discharge pulse. The detailed data for 1978 is not available but the input discharge was at an almost identical stage. 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 most coincident at Traverses 1 and 2 and later discharge peaks would also have assisted in promoting the faster dye velocity movements observed in 1979. The discharge for the Gauging Station GS 821 018 for the period 1800 on 13 February to 0900 on 15 February is illustrated in Figure 2.28.

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 dispersion conditions.

In order to fully utilize the data from field experiments of this type the literature on dispersion studies together with associated statistical techniques should be employed wherever possible. An introduction to the available methodology is given in Appendix 1.

2.6 Variations of Dye Concentration with Depth

The 1978 report discussed the possible variation of dye concentration with depth. If significant variations do occur between surface and depth samples there is an obvious importance for dispersion studies. In rapidly flowing channel flow, of the type generally found in the Magela Creek above Site 3, the dye concentration does not exhibit marked variations; the only exception may be close to the actual injection point. However, where the flow is slower the 1978 observations suggested that vertical mixing can be poor.

Sample collection in 1979 attempted, wherever practical, to investigate variations in concentration with depth. Comment has been made throughout this section on those results, see especially Sections 2.3.2 and 2.3.3. Two depth profiles were also sampled in Hidden Billabong and the results are shown in Figure 2.29. In the first of these profiles there was little variation with depth except that the surface sample exhibited a much higher concentration. This could in fact, be related to the temperatures which are also shown on the figure. However, a second profile, which was taken several hundred metres distant but still in open-water billabong conditions, does not show this higher surface concentration despite a very similar temperature profile.

These observations can be compared to those illustrated in Smith, Young and Goldberg (1978b) as Figure 75. The 1978 observations
also showed that some profiles in open-water billabongs exhibited little or no variations with depth while others showed very marked variations.

Thus it is not possible to offer any clear account of these variations, but to again stress that tracer sampling exercises should, wherever possible, include depth samples.

2.7 Summary and Conclusions

i. The experimental design, quantity of dye used and the sampling scheme employed were successful in that they provided adequate data to obtain information on the time of travel and the overall pattern of dispersion. The detailed information has been presented earlier in this section.

ii. A comparison of the data to that obtained in 1978 shows that the velocity of the peak was very much faster in 1979 and this is associated with the flood pulse that moved down the Magela Creek System soon after the dye injection.

iii. The poor horizontal and vertical mixing observed in 1978 for the Traverse at the upstream end of Mudginberri Billabong (Traverse 1 of this report) were confirmed. However, it was established that was a local phenomenon due to the location of that traverse at a site where the influent waters from the main Magela Creek were poorly mixed with the deeper water of the Billabong.
iv. The 1979 observations included two traverses (numbers 3 and 4) across the whole width of the flooded sections of the Magela Creek System where thick aquatic vegetation and paperbarks could be expected to affect the pattern of dispersion. The initial conclusions are that where such traverses include open sections, these transport greater dye mass than the parts of the cross section that are weed choked. There is also some evidence that initial dye arrival tends to be concentrated in the surface layers but as the peak passes dye can be detected throughout the whole cross section. These observations could be improved by combining the dye concentration values with point velocity readings to obtain dye loadings for specific points within the traverse cross sections.

v. The sampling was curtailed some seven days after input although there is no doubt that with the quantity of dye used and under the prevailing hydrological conditions that observations could have continued for several days longer, which would probably have allowed the dye to be traced in a meaningful fashion for several further kilometres.

The information gathered from this experiment should extend the existing knowledge on the times of travel and dispersion within the Magela Creek System. In addition, the experiment was designed to investigate sampling strategies and methods to assist with further studies that may be undertaken by the Water Division. Discussion of possible design for such further work is given in Section 6.
3. **Dye Dispersion Experiment at Gulungul**

3.1 **Introduction**

The dye dispersion studies in the main Magela Creek System described in this report, with the comparable experiment of March 1978 reported in Smith, Young and Goldberg (1978b), represent one application of the technique. The size of the dye input, the duration of the experiment and the associated labour requirements are large. Fluorometric methods have other applications which can be of assistance in obtaining data related to the potential water pollution problems associated with uranium mining and milling. One such application is to use the dyes to investigate circulation and dispersion in the smaller billabongs.

To gain experience of this type of application, dye was injected into the stream feeding the Gulungul Billabong in order to investigate dispersion in the Billabong itself. The experiment was undertaken to illustrate the methodology and to suggest possible experimental designs that the Water Division could use for subsequent studies. It should be stressed that in any future application the sampling design would be modified to obtain answers to specific problems. The pilot experiment had the following general aims:

a. to investigate the time of travel through the actual billabong, and
b. to gain information on the mixing of the dye both spatially and with depth.

3.2 **Experimental Details**

One litre of 20% Rhodamine WT solution (200 g of dry weight dye) was injected at 09:25 on 8 February into Gulungul Creek some 2.5 km upstream of the main billabong. The actual injection site
was located just downstream of a road crossing where the Creek flows in a well defined channel. The dye was poured from a container into the centre of the channel and the injection time can be regarded as instantaneous.

Sampling sites were established downstream in order to ascertain information on travel time and dispersion. Two sites, referred to as Stations 1 and 2, were located in the stream section and the remaining sites in the actual billabong and in the outflow stream downstream of the billabong. A sketch map of the locations is given in Figure 3.1.

Station 1 was selected at a location relatively close to the injection point, but where the Creek was still confined in a simple single channel. This enabled information to be gained on the time of flow in the channel section and also an accurate estimate to be obtained of the discharge of the inflow stream.

Station 2 was also upstream of the main billabong, but at a location where the stream had a width estimated to be about 200 m and flowed through an area of flooded paperbark.

Eleven stations were marked by buoys in the main Billabong and in the outflow channel. The central portion of the Billabong is open water, but the greater part of the surface area is covered by water-lilies and other aquatic plants. Sites 7 and 8 were located in the outflow channel. An automatic water sampler was located close to Site 8 during the earlier part of the experiment. The approximate location of the sites and the area of open water is shown on Figure 3.2.

There was relatively little variation in the depth of water in the billabong during the course of the experiment. The staff gauge indicated that the extreme variation from 8 to 11 February was only from 2.71 to 2.63 m and generally the level was falling.
In order to investigate vertical mixing samples were also collected at depth in the Billabong using simple hand depth-samplers. A systematic depth survey of the Billabong was not undertaken but the depths at the sampling sites is given in Figure 3.2. Away from the limited area of open water the aquatic plants were occasionally so thick as to make the collection of depth samples difficult.

3.3 Sampling Sites and Results

3.3.1 Station 1

Station 1 consisted of a well defined channel with shallow flooded areas on either side. The main channel was sampled at 5-minute intervals from 0925 until 1130. The sampling during this period was by hand from a boat moored in the centre of the channel. The dye concentrations are given in Figure 3.3.

In addition to the detailed hand sampling an automatic sampler was also installed in the main channel. This sampled at a 30 min. interval from 0938 to 1408 on 8 February. The analysis of these samples enabled the 5 min manual sampling data to be extended. Figure 3.3 presents the dye values obtained at Station 1. The combined dye concentration data was used to calculate the discharge of the channel; the result was 2.3 cumecs. The details of the method of calculation for dye dilution gauging are given in Appendix 2.

The time of travel in the channel section between the injection point and Station 1 is between 30 and 35 minutes for the first appearance, approximately 40 minutes for the dye peak and 65 minutes for the dye centroid. The distance between the input and Station 1 was not accurately measured, but employing estimates based on the air photos the distance is 500 m, this gives velocities of approximately 45, 37 and 23 cm/sec for the first appearance, peak and centroid respectively.
Occasional samples were also taken from the shallow flooded areas away from the main channel. Visual observation suggested that these were stagnant but traces of dye, up to levels of approximately thirty times background, were obtained. In some field circumstances it would be of value to establish if these backwater areas, with no apparent flow, were in fact connected to the main channel flow and the capability of detecting extremely low concentrations of dye is useful in this respect.

3.3.2 Station 2

This Station was established in flowing water upstream of the Billabong, but in an extensive area of flooded paperbark. The main samples were collected manually from a moored boat at approximately 10 minute intervals from a point estimated to be in the major flow path. Samples were collected from two subsidiary sites within this area of flooded paperbark forest. One was some 20 m from the main flow line at Station 2 (termed Station 2 East) in shallow water close to the margin of the flooded area. The other, Station 2 West, was some 50 m further into the main mass of flooded paperbark.

The dye concentration values for Station 2 are given in Figure 3.4. The times of travel for the dye first arrival peak concentration and centroid are 90, 145 and 190 minutes respectively. The peak dye concentration is close to 10 µg/l. The velocities, employing estimates of the distance from the sketch map in Figure 3.1, are approximately 35, 22 and 17 cm/sec.

The first arrival of the dye at Station 2 East is estimated to be 150 mins and for Station 2 West 210 mins.

The interest in these observations is not the exact details obtained, but the potential of the method to yield information for the time of travel and dilution for specific points within a complex channel cross-section.
3.3.3 Sites 1-11

Stations 1 and 2 are associated with the input channel of Gulgulgul Billabong and Sites 1-11 with the billabong and its outflow channel. Samples were collected from all, or a selection, of these sites on ten occasions between 1200 on 8 February and 1100 on 11 February. In addition an automatic sampler set to take samples at 30 min intervals was located close to Station 8 for the period 1825 on 8 February to 0825 on 9 February.

All the manually collected samples were at background values until the sample run at 1000 hrs on 9 February. However, by that time all the sites, except Sites 9 and 10, showed the presence of dye. The variation in dye concentration was large and ranged from a trace to 1.27 µg/l. The spatial variation of the dye concentration for the surface samples collected at 1000 and 1445 on 8 February, 1615 on 10 February and 1100 on 11 February is illustrated in Figure 3.5a, b, c and d. The number of sample runs is insufficient with the exception of Site 8, to draw detailed time series curves of dye concentration for individual sites. The dye concentration values for Site 8 are illustrated in Figure 3.6 which included both samples from the automatic sampler and manual samples.

The time taken for the dye to reach the outflow from the lagoon is some 17 hrs for the first arrival, 22 hrs to reach the peak concentration and 33 hrs for the contoid. The peak concentration recorded at this site was 1.23 µg/l. Thus, if we assume that the dye is simulating a soluble pollutant from a point source, the salient information regarding time of travel and dilution can be easily obtained.

There are insufficient samples for the other sites to give a detailed picture of dispersion within the Billabong. However, Sites 2, 3 and 5 exhibit higher concentrations than the other sites.
and it can be stated that these lie close to the main flow path through the Billabong. However, Sites 1, 4, 6, 9 and 11 exhibited clear positive values together with Sites 7 and 8 which were in the outflow channel. Of these Sites 4 and 9 were close to the edge of the Billabong and in locations with a prolific growth of weed. The only site which did not show a clear positive dye value was Site 10. In addition to these sampling sites a number of samples were collected from a location inshore from the gauge, the depth of water was about 0.3 m and there was a cover of aquatic plants. This site recorded values of up to 0.64 µg/l.

From the limited data (no samples were collected during the hours of darkness) it would appear that there is a broad major flow line through the billabong, but that dye reaches nearly all parts of the system regardless of depth of water or thickness of vegetation. The quantity of dye passing the flow line sites (especially 2, 3, 5, 7 and 8) will however, be considerably greater than for the other sites.

Figure 3.7 and 3.8 are reproductions of computer plots of the dye concentration values for the samples collected at 1000 and 1400 hrs on 9 February. These can be compared to Figure 3.5 which give the actual point observations. The computer plots are included as they represent a further extension of the work which could be of value in situations where there is a greater intensity of sampling points.

3.3.4 Depth Samples

Additional samples were collected at depth on a number of the sampling runs. Normally these samples were from a depth of 1.0 m but occasional samples were collected some 10 cm above the bottom. There were very considerable variations in the dye concentrations.
with depth and no clear pattern was discernible. For example, in the samples collected at 1000 on 9 February Site 3 had a surface value of 1.27 μg/l and a 1.0 m depth value of 0.65 while Site 5 had a surface value of 0.71 and a depth value of 1.05. These depth variations are not due to errors in analysis as the outflow channel sites, with a strong current, were fully mixed with depth and surface and depth differences were normally less than 10%. More intensive sampling may have resulted in the appearance of a clearer pattern of these variations, but what is certain is that detailed work on dispersion in billabong situations should include depth samples. This is especially to be recommended if the dye is simulating pollution movement in relation to possible contamination of the aquatic plants. A limited survey was made of the water temperatures of the sampling sites in relation to depth, but no clear relationship between variations in dye concentration was established.

3.4 Conclusion

i. The overall sampling strategy and design were satisfactory and the data is such that information on the time of travel and dispersion of a point injection can be obtained. If the dye is used to simulate a soluble source, it is a relatively easy matter to calculate the dilution that would occur at specific sites.

ii. The design could be improved for experiments used to answer specific queries, such as the dilution at particularly sensitive sites. Also, the value of the work would be greatly enhanced if the experiments were repeated under differing flow conditions. It must be stressed that the results reported above, which are
for an input of some 2.3 cumecs and a Billabong gauge
level of approximately 2.7 m, should not be extrapolated
to markedly different hydrological conditions.

iii. The greatest constraint is the labour requirement to
collect the samples, the analysis is relatively rapid.
Also the nature of the work, which involves the use of
small boats or canoes, is difficult during hours of
darkness. Thus the use of automatic water samplers is
strongly recommended for critical sites.

iv. For detailed work, depth samples should be collected
at least until a pattern emerges in the results in
relation to surface samples. This is strongly recommended
for billabong sites, but is much less of a problem for
flow in well defined channels.

v. If answers are required to a narrow range of specific
problems, the labour and boat requirements can be very
much reduced and more reliance placed upon the use of
automatic samplers.
4. Dye Dispersion Experiment at Jabiluka Billabong

4.1 Description and Results

In order to provide preliminary information on the hydrology in the vicinity of the proposed Pancontinental outflow, a small scale dye experiment was conducted at Jabiluka Billabong.

Five litres of Rhodamine WT dye was dropped from a slowly moving airboat at 0932 on February 20 1979. The dye was released from the east end of the flood plain at a bearing of 260° magnetic over a distance of 300m at a position south of the Billabong, as shown in Figure 4.1.

The sampling was undertaken along three traverses across the Billabong and samples were collected both from the surface and at depth. The Traverses were designated as A, B and C and there were five stations in the open water area of the Billabong on each. The location of traverses and stations is shown in Figure 4.1. The stations were numbered from the east bank. Samples were also collected along extensions of the traverse lines to the west of the open section of the Billabong. As this area has a thick cover of aquatic vegetation the samples were collected from an air-boat.

Both visual observations and fluorometric samples indicated that all the dye was channeled onto the open section of the Billabong and no dye spread into the flood plain along traverses A or B i.e. those areas with aquatic vegetation. There was a residual dye concentration of 0.25μg/l at all stations except those in the open area of the Billabong which is interpreted as the remnant fluorescence from the main experiment of February 11. This remnant dye seems to have been flushed out of the open water area of the Billabong itself.
Details of the results at Traverses A, B and C for both surface and depth samples are given in Figures 4.2 and 4.3. Sampling at traverse A indicated that the peak dye concentration of 7 μg/l arrived at 1150 and that it arrived:

i) in the western half (i.e. the deeper part) of the open water section of the Billabong and

ii) at a depth of 2.5 m below the surface.

Sampling at Traverse B commenced at 1228 and appears to have missed the first arrival of the dye. Similarly the sampling at traverse C, which commenced at 1300, seems to have been coincident with, or just a very short while after, the peak passed the gauging station (821017) situated along this traverse. Based on those times the approximate flow speed is estimated to be 7.2 ± 1.4 cm/s. If we further assume a 600m² cross-section for the open water section (i.e. 120m width and a 5m mean depth) we obtain a flow estimate of 43 cumecs.

The major flow lines obtained from the analysis of the samples and from the air photographs of the visible dye are also shown in Figure 4.1.

4.2 Interpretation

It is most likely that the funneling into Jabiluka Billabong, and the original penetration at a depth of about 25m 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 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.

Though the results indicate that the intruding fluid moves towards the surface as it propagates through the Billabong, it is not certain whether it does this because

1) the surface waters at the northern end of the Billabong are more dense (colder) than the surface waters at the southern end or whether

ii) substantial mixing takes place between the intruding dye and the less dense Billabong water.

On the basis of our results for the dye concentrations at traverses A, B and C one would tentatively argue in favour of the first of these two possibilities, since the dye did not seem exceedingly diluted in travelling downstream.

It is uncertain whether this funneling and stratified intrusion is a permanent feature of the flow. It seems to depend on the preferential heating of the slow moving Billabong surface water and flood plains water. Presumably, when this heating does not take place - for example, during prolonged storm periods, or when there is substantial wind induced mixing of the Billabong waters then one could expect funneling into Jabiluka Billabong to be absent. Within this context it is of interest to note results during earlier experiments conducted by the AAEC on Jabiluka Billabong (Eady, 1976) in which temperature measurements on February 19 and 20, 1976 revealed isothermal temperatures from the surface to the bottom; the temperature being 30.2°C at 1545 on February 19 and 39.0°C at 0958 on February 20.
5 Comparison of Dye and Tritium Tracing

5.1 Introduction

The merits of fluorometric dye tracing are several. The instrumentation can be easily used in the field and it is possible to determine suitable dyes in very low concentrations. The major query is the rate of dye decay in natural waters.

In general there is agreement that rhodamine WT has a very low decay and as the dye is normally employed for dye dilution gauging this question has been the subject of quite extensive field experimentation. This work was initially undertaken by the United States Geological Survey, Water Supply Division, and the results can be summarised by stating that for dye dilution gauging the decay is small over time periods of up to 24 hours or so. Indeed, in dye dilution gauging experiments of short duration the decay loss is normally assumed to be zero. However, where dyes are used to trace water movement and dispersion for longer periods there is undoubtedly a noticeable decay rate. This could be of practical importance if the method is employed in any form of budgetting.

There are a number of reports in the literature of experiments investigating dye loss or decay under laboratory conditions. From these it is clear, for example, that there is a very considerable 'loss' of rhodamine WT for experiments where low concentrations of the dye are passed through columns containing soil especially when the organic content is high. A good review of these laboratory experiments is given in Smart and Laidlay (1977). In contrast there are very few accounts of field experiments of several days, or weeks, duration where the Rhodamine decay has been measured or estimated. Experiments which yield some measure of this decay has been conducted by CPES and
for a field situation with close controls on the discharge a decay rate of about 1% per day was obtained (see Smith, 1978). A study in the Georges River, NSW indicated rates of some 3% per day (Warner and Smith, 1979 in press). The American literature suggests that the decay rate of Rhodamine may be close to 3% per day. All workers would agree that the decay rate will vary from one locality to another, and is likely related to the concentration and mineralogy of the sediment, the organic content and possibly duration and intensity of sunlight.

5.2 The 1978 Experiment

The field experiments undertaken in the Magala Creek system in March 1978 included a comparison of rhodamine and radio-isotope methods. This was only possible due to the valuable co-operation given by the AAEC staff who were working in the area and by the assistance from Pan Continental in making available their laboratory equipment at Ja Ja. In the 1978 experiment 3 Curies of Tritium were injected at the same time as the main dye injection. Eighty-nine samples were analysed using the Tri-carb Liquid Scintillation Spectrometer installed in Pancontinental's laboratory. The CREC team carried out the laboratory work but the techniques employed were identical to those by the AAEC team.

The results are presented in Smith, Young and Goldberg (1979b) and in Goldberg (1978). The overall conclusion was that for samples collected more than 21 hours after injection the tritium concentrations were too low for a meaningful statistical comparison to be made with the dye values (the dye was detectable for at least 7 days after injection). For periods up to 21 hours after injection no significant dye loss was apparent.
Thus, in summary the 1978 dye/tritium experiment was technically a success but the quantity of tritium injected was insufficient to yield information on the decay rate of rhodamine under field conditions. It should be noted that a basic assumption in the experimental design was that tritium is regarded as fully conservative, given that it has a half-life of 12.26 years.

5.3 The 1979 Experiment

The basic design and analytical methods were comparable to those in the 1978 experiment. In this case 10 Curies of tritium were injected at the same time as the 10kg of dye. Duplicate samples for dye and tritium analysis were collected. The samples for Traverse 4 (Kelly's Line) were analysed for tritium by the AAEC team soon after collection and the remaining samples by the analytical section of the Water Division, using the same equipment and methods as detailed for the 1978 experiment. Ninety-seven samples were analysed from Traverse 4 and 79 from other parts of the Magela Creek System. The details of the later samples are given in Appendix 3. The results for Traverse 4 were presented in graphical form and full details of standard deviation etc. are not available.

5.4 A comparison of dye and tritium concentration

The dye and tritium concentration values for all the samples (but not including those for Traverse 4) are plotted in figure 5.1. The dye values are in micro-grams per litre (μg/l) and the tritium values in micro-Curies per cubic metre (μCi/m³). Since 10 kg of dye were injected simultaneously with 10 curies of tritium, the numerical values of the two readings should be directly comparable. The correlation coefficient for this graph is 0.99.
but for the purposes of the experiment the points of interest are
the degree of reproducibility between the results and possible
information on the decay of the rhodamine concentrations with
time.

Figure 5.1 clearly shows, at least for the higher concentrations,
that the tritium values are greater than the corresponding dye values.
However, the higher concentration values are all from the earlier
part of the experiment where the travel time was less than 24 hours.

Figure 5.2 plots the same data as Figure 5.1 except that all
points with a tritium concentration of greater than 1.2 mCi/m$^3$
are omitted. In this case the samples with the lower values have a
marked tendency for the rhodamine concentrations to exceed those for
tritium.

In order to obtain a measure of the relationship of rhodamine
to tritium concentrations the ratio of dye to tritium was plotted
against time. The results are shown in Figure 5.3, tritium values
with standard deviations that could yield values of less than zero
are omitted. As far as a simple interpretation of the scatter of
points is possible the indication is that the ratio increases with
time, i.e. there is an apparent decay of tritium rather than
rhodamine. This is reinforced by Figure 5.4 which plots the
concentrations for samples collected three days or more after
injection.

5.5 A comparison of dye and tritium concentrations for specific
sites

Figure 5.5 shows the dye concentration values at an hourly
interval from an automatic sampler located at Site 4. It also
shows, for a limited number of samples, the corresponding tritium
concentrations. All the samples were collected during the first
24 hours after injection. The general shape of the two curves is similar but for values greater than 2.0 µg/l the tritium samples are significantly higher.

A similar set of samples collected at 4 hour intervals from Traverse 6 is illustrated in Figure 5.6. The earlier form of the dye concentration curve is plotted and it has, as its general form, a regular falling concentration. The tritium values for the last 10 samples are also plotted, in this instance together with one standard deviation. The form of the tritium curve is irregular and the later samples tend to indicate that no detectable tritium was present. The background dye concentration values would be in the range of 0.025 to 0.055 µg/l.

Figure 5.7 is for two of the sets of samples from Traverse 4, Kelly's line, and again shows both dye and tritium values. A similar pattern emerges with the tritium values exceeding those of rhodamine for the higher concentrations, and for lower concentrations the tritium appears to give zero values while the dye concentrations are above background levels.

5.6 Conclusion

(i) the quantity of tritium employed was insufficient to allow a detailed comparison with the rhodamine. This is especially the case when the dilutions are large and therefore for samples collected after three days or so the tritium values are small and their standard deviation large.

(ii) the experiment fails to give any clear indication of a likely decay rate for the dye. Indeed, in those cases with low concentrations the dye is often detectable when the tritium is not.
(iii) It may well be that under the prevailing conditions of extreme evaporation that the assumption that tritium is fully conservative is not strictly true.

(iv) For most practical purposes of dispersion tracing within the Magela System it would appear that Rhodamine does not suffer from any unduly fast decay rate. However, care should be exercised if the dye values are used for budgetting for periods in excess of several days after injection.

Detailed discussion comparing the results have not yet been held with the AAEC but the practical conclusion is that fluorometric tracing employing rhodamine WT in the waters of the Magela Creek system is not unduly affected by decay.
6. Suggestions on the Application of Fluorometric Methods to Dispersion Problems with the Alligator Rivers Region

6.1 Introduction

The initial field experiments, undertaken in March 1978 on behalf of the Supervising Scientist, were designed to establish if fluorometric dye tracing was a viable field technique to study dispersion problems in the Magela Creek System. This work was described in Smith, Young and Goldberg (1978b) and the technique was shown to be of value to such studies.

The field experiments in February 1978 were under the auspices of the Northern Territory Water Division. In addition to adding to the information gained in 1978 the work was also aimed at demonstrating the methods and techniques to the staff of the Water Division so that future studies could be carried out by that body. This is important for two reasons. Firstly, because for many purposes the most useful applied data is linked to periods of high discharge and the frequency of such events is such that they can only reliably be carried out by workers based in the actual region. Secondly, the technique has a number of applications to problems of water pollution other than attempting to simulate the time of travel and dispersion from discharges into the main Magela Creek System.

This section will suggest:

(i) Instrumentation and methods of approach for experiments similar in approach to those undertaken in 1979.
(ii) An outline of other possible applications that may be of value to a broader range of studies in the Alligator Rivers region.
6.2 Instrumentation

The merits of fluorometric dye tracing are that accurate determinations of dye in very low concentrations can be made very quickly and, if required, the analysis can be undertaken under field conditions. It MAY be of value to briefly review both the dye and the instrumentation.

6.2.1 Fluorometric Dyes

There is a wide range of possible fluorescent dyes but there is no doubt that for the study of surface water dispersion Rhodamine WT is the most suitable. Its major advantages are its relatively slow rate of decay under field conditions and the relatively small background fluorescence in natural waters.

The experiments undertaken to compare Rhodamine WT and tritium, in order to ascertain the decay rate of the dye in the waters of the Magela Creek system, were not fully satisfactory. It has however, been demonstrated that for practical purposes, Rhodamine WT can be regarded as conservative for periods of several days. An estimate of likely decay rates would be between 1 and 3% per day.

The background fluorescence in the appropriate wavebands for Rhodamine WT in the area are low. These should be determined for each individual experiment, and ideally for each site, but are likely to be in the range 0.02 to 0.07 µg/l. This range is comparable with values for natural waters obtained elsewhere in Australia and overseas.

Possible disadvantages of Rhodamine WT are that it is only supplied in liquid form and only limited stocks are held within Australia so that major experiments need to be planned well in advance.
Except for specialized applications when it may be useful to use multiple dye injections, (these are briefly discussed in section 6.5.1). Rhodamine should be employed. It is also acceptable on toxicological grounds but care should be taken not to confuse the dye with Rhodamine B. The latter dye is supplied in powder form and was formerly used for fluorometric tracing but it has inferior properties to Rhodamine WT and is not acceptable on toxicological criteria.

6.2.2 Fluorometers

The best instrument currently available that is designed for field use (it can also be used most satisfactorily as a laboratory instrument) is the filter fluorometer manufactured by Turner Designs. This is the instrument obtained by the Water Division for future dye work and it is not the aim of this account to produce a user's manual. This instrument has many advantages over the earlier Turner Associates Model III fluorometer but it is essential that the operators are fully familiar with the standardization procedure. The instrument can be satisfactorily powered in the field either by batteries or by a small Honda generator. Samples can be analysed rapidly at a rate well in excess of one per minute.

The instrument can also be supplied with flow-through attachments so that it can be boat mounted and the sampling hose used to measure fluorescence at depth, say in the deeper billabongs. The flow-through attachment and pump can also be combined with a chart recorder to obtain a continuous record of fluorescence at a single site. For some applications these facilities could be of considerable value e.g. where a continuous record of fluorescence at one site is required. However, for applications where a number of sites are being monitored it is frequently more useful to have the fluorometer available in the field so that a selection of samples can be quickly analysed from several sites and the sampling pattern,
both in terms of time and location, modified as the experiment progresses.

There are two areas where particular care should be exercised:

1. As the dye can be detected at very low concentrations (approximately 1 part in $10^{11}$) extreme care should be taken that there is no contamination from the input site to the sampling sites. It is recommended that wherever possible the person responsible for the injection takes no part whatsoever in the subsequent sampling.

2. For detailed work it should be remembered that fluorescence is quite markedly affected by temperature. In practice, this means that the analysis should be undertaken in a room or laboratory that has a small temperature variations. Also the samples should be allowed to equilibrate with the laboratory temperature before analysis. For field purposes the instrument can be used to obtain an approximate values of fluorescence useful in modifying the full sampling pattern but such samples should be re-analysed under near constant temperatures conditions.

6.2.3 Automatic Recorders

The limitation with the field applications of the dye tracing is not the time required for analysis but the time and effort expended in the collection of samples. This is particularly relevant where dye experiments extend into the hours of darkness or when samples are required over an extensive period of time at remote sites. The nature of the terrain in the Alligator Rivers Region is such that these points are especially pertinent. To some extent the problems can be lessened by the use of automatic water samplers. It is strongly recommended that these are purchased and used wherever possible. There are a number
of models currently available and distributed in Australia. Perhaps the most reliable and field tested of these are the Manning automatic samplers that are manufactured in the U.S.A.

The majority of battery run automatic samplers can take up to 25 separate samples and the sampling interval can be adjusted from one sample every few minutes to one sample every 24 hours. The batteries supplied, which are rechargeable, are sufficient to take 50 or more individual samples. The cost is approximately $2,000 but the savings over the alternative of manual collection are particularly favourable in terrain where transport is by air-boat or helicopter. Clearly, the samplers can also be used for other forms of water quality sampling.

6.3 Applications of Dye Techniques to Surface Water Pollution Problems

Basically the dyes are injected to simulate the movement of soluble pollutants. The design of any individual experiment should clearly be aimed at producing information related to one or more specific problems. However, the aim of the three experiments undertaken in February 1979 was to illustrate experiments that differed in scale and design. It may be useful to briefly review these aims.

6.3.1 The Main Magola Channel Experiments

This, by any standards, was a large experiment as regards the mass of dye used, the time over which the dye was traced and the various applications illustrated. It was a point source with a near instantaneous input. Sites were established to investigate the speed of flow in the initial fast flowing section of the Magola Creek and as this portion of the channel has an anastomosing form it was of interest to see if the flow in the component channels was well mixed. Thus samples were collected at short time intervals (5 minutes or so) to produce a well controlled concentration curve.
for each sampling site. It was found that the flow was generally well mixed across the channels so that as a by-product of the dispersion data the information could be used to produce an estimate of the actual discharge. That is the same experiment was essentially a dilution gauging exercise which is, in fact, the reason why fluorometric dye methods were first developed.

As the input needed to be large in order to trace the dye over considerable distances it was possible to take hand held aerial colour photos which gave visual information on the dye dispersion for the first few hours of the experiment. It must be stressed that for most dye applications the quantities used are very much smaller and fluorometric techniques do not necessitate turning large volumes of water red! However, for these larger experiments the 'by-product' information obtained from visual observations is of considerable practical value.

Once the dye had reached Mudginberri Billabong the flow velocity and flow form were very different. Here much of the interest is to investigate the lateral and vertical mixing. Some of the key pollution questions are concerned with establishing if the dye (or soluble pollutant) follows distinct flow lines or whether it disperses over the whole flooded cross section. Similarly there is interest in whether the dye is mixed in relation to depth, this is particularly the case where there is a thick cover of aquatic vegetation. The sampling design here should clearly be modified to investigate the specific query and the sampling timing and distribution adjusted accordingly.

In the lower sections of the system, below Ja Ja, manual sampling can only be undertaken by the use of air-boats which should ideally be linked to the use of automatic samplers. It was established
in 1978 that, if required, the fluorometer can be mounted, together
with a small generator, on the air-boat. The main experiment showed
that the flow lines in this lower section showed a distinct bifurcation.

6.3.2 Extensions of the Main Magela Channel Experiment

The obvious extension of this experiment would be to repeat
it under higher stage conditions. Depending on the aims it is
suggested that much of the relevant information could be gained from
a very much smaller number of sampling sites than was used in 1978 and
1979. A suggested strategy would be to maintain Site 1 (at gauging
station GS 009) and if possible to check that the dye concentration
was broadly similar over the whole of the channel cross section. It
might be possible to combine this with routine flood river gauging.

The next site could be at the gauging station just upstream
of Mudginberri Billabong (Site 3 of the 1979 experiment). If
information was required from the billabong itself a site somewhere
near Traverse 2 would be recommended. Clearly sites at the upstream
end of the billabong are totally unsuitable.

The installation of an automatic sampler set on an hourly
sampling interval at gauging station GS 023 would be another
convenient site. At times of high flow this could conveniently be
sited at the top of the gauging structure.

It would be of interest to investigate the lateral and vertical
dispersion in the section of the system below Mudginberri Billabong.
This is a rather tedious piece of fieldwork but the Traverse already
established, and referred to as Traverse 3, in this report might well
be convenient.
Sites close to the shore at Ja Ja should be avoided as these appear to be positioned in an area of backwater flow.

Some of the major interest may be in whether the flow in the section below Ja Ja maintains the bifurcated pattern described in this report. This would ideally be investigated by the use of automatic water samplers either firmly secured in trees in the flooded section or positioned on moored boats. The former would appear to be a convenient and practical method. It is recommended that any air boat sampling sites are marked by floats.

If this form of experiment is repeated under high stage conditions it is not thought necessary to greatly increase the amount of dye employed as the flow will be faster and the dye pulse will have a narrower base. It should also be possible to detect the dye in Jabiluka Billabong.

If information is required as to the speed of flow and dispersion further downstream than Jabiluka Billabong consideration should be given to a second dye input, perhaps in Jabiluka Billabong, rather than increasing the already large input in the upper part of the Magela System.

The value of the work under high discharge conditions is stressed but since this will coincide with difficult field conditions it is our opinion that emphasis on obtaining good information on a limited number of more accessible sites should out-weigh attempts to repeat observations from the larger numbers sites used in the 1979 experiment.

6.4 The Gulungul Experiment

This was essentially an example of a more local application of the Main Magela Experiment. Again the injection site chosen enabled an accurate estimate to be made by dye dilution methods of
the input stream discharge. The major information to be gained from this smaller scale experiment would be detail regarding the dispersion of the dye in a smaller lagoon or billabong. This detail could include work that may be closely related to possible contamination problems associated with aquatic flora and fauna. For example, information could be gathered on the degree to which the dye reaches the shallower and more confined margins of the Billabong. The design could also be usefully employed to establish the optimum location of stations that would later be used for detailed water quality collecting sites. This was the basis of the work described by Smith (1978) for the wildlife ponds at Tidbinbilla in the ACT.

Again the most useful information could probably be obtained by a repetition of this experiment under high flow conditions. The interest would be to establish how quickly the water passed through the billabong and particularly if it followed a narrower flow path. The combination of manual sampling with the use of automatic samplers is again recommended.

6.5 The Jabiluka Billabong Experiment

This was undertaken to investigate the problems likely to be encountered by dispersion in what was considered to be a slowly moving deeper water mass. It also illustrated the value of air photography to distinguish flow lines when the dye was still in its visual phase. Additionally the possibility of injecting the dye in a line form rather than from a point source was illustrated.

Perhaps the most useful aspect of this experimental design was to demonstrate the importance of depth sampling.
6.6 Other Possible Applications of Fluorometric Techniques

The initial development of fluorometric techniques in hydrology was in the field of dye dilution gauging. This was then extended into broader fields of surface water dispersion of which the experiments of 1978 and 1979 are examples. The technique has been used widely in these two fields over the last 15 years or so. There are however, other more recent applications which could be of value in the general field of hydrological effects of uranium mining and milling in the Alligator Rivers region.

Thus an introductory outline will be given to possible further applications under the following three headings:

1. Groundwater tracing
2. Soil tracing
3. Modifications of the dye dilution method.

It must be stressed however, that while all three of these applications could be of considerable value they would need some preliminary fieldwork in the region itself before they could be firmly recommended as having any form of routine application.

6.6.1 Groundwater Tracing

The use of fluorometric dyes for groundwater tracing does not have the long period of experimentation that is the case with surface water dispersion studies. However, in favourable circumstances there is no doubt that the technique has considerable practical value. In groundwater situations where the conductivity is relatively fast the method can be easily applied. This can either be where inter-granular (primary) conductivity or secondary conductivity related to fissure flow are well developed. In fractured limestone bedrock dye traces over distances in excess of 30 km have been successfully carried out, a broad review of limestone groundwater tracing is given.
in Smith (1977). More recently local groundwater dispersion studies from borehole to borehole have been reported in non-limestone aquifers. For example, the studies reported by Smith and Jacobson and Thorpe in the Proceedings of the AWRC Conference in Groundwater Pollution in Perth 1978. These later studies may be pertinent to problems in the Uranium Province.

The ideal situation would be to ascertain if groundwater movement has a fast flow component which may be superimposed upon a regionally low groundwater conductivity. The dye would be injected into boreholes in the area under study (the Ranger pond sites would be a case in point) and samples collected from neighbouring boreholes to establish the speed of flow. The work could be attempted under natural flow conditions or combined with standard pumping tests. Such experiments could be improved if more than one dye could be used simultaneously. In that case a probable maximum of three boreholes in a local area could be injected with differing dyes and the tests carried out simultaneously, i.e. each water sample would be tested for the presence of each dye by changing the filter combinations in the fluorometer.

The strategy of such experiments is that if the dye is found in the sampling boreholes the connection is likely to be via some form of fissure flow. If this is the case likely groundwater flow rates may well be so rapid as to give cause for concern for subsequent surface water contamination. The shortcoming with the strategy is that a lack of connection between borehole and sampling boreholes does not categorically indicate that connections do not exist.

A 'by-product' of such experiments is that by monitoring the rate of dye decay in the injection borehole dye-dilution techniques
(see Levis et al., 1966 for details of the calculations) can enable basic information of the conductivity to be obtained. Again the method has particular merit in drawing attention to likely fissure flow intersected by the boreholes concerned.

Thus the method could be investigated for use in shallow bedrock situations but would be of considerable value in investigating groundwater flow properties in boreholes in superficial rock types such as sands or gravels.

The merit of these fluorometric groundwater techniques is in demonstrating situations where fast groundwater flow can be expected and it is particularly pertinent to local situations where groundwater pollution could be important.

6.6.2 Soil Tracing

This is used as a broad term to incorporate all forms of water movement in superficial layers other than those included in the normal heading of groundwater movement. This is a difficult environment for the use of fluorescent dyes as there are very considerable losses onto soil and organic material by absorption. However, in recent years it has been demonstrated that at the local scale fluorometric methods can be used to trace both vertical and lateral water flow in soils. In these applications, due to the dye losses, budget studies are not appropriate.

At its simplest dye can be spread onto a limited area of soil (perhaps 1-5 square metres) and the resulting distribution pattern after rainfall measured. This can either be by digging a vertical section after the rainfall and analysing soil samples for their dye content (to some extent there is a visual staining) or if the study is on a slope by investigating through-flow for dye in pits dug.
downslope. The natural rain events can, with care, be simulated by artificial watering.

Again the possible application of this methodology is best considered in relation to local sites where details of soil water movement are particularly critical. Clearly if the soils are coarse textured or clearly contain macro-pores and fissures the method is more likely to succeed.

Detailed review literature on such applications are still relatively few but recent experiments in Australia and overseas are such that it may be thought useful to investigate the potential in the Alligator Rivers area particularly in relation to the Ranger site.

This form of application is one of the few where Rhodamine WT may not be the best dye.

6.6.3 Surface Dilution Gauging

The standard method for dye dilution stream gauging depends on the sampling site being fully mixed throughout the cross section. However, the problems of gauging the natural flows especially in the lower parts of the Wagela Creek System are such that none of the recommended gauging procedures are satisfactory whether current meter, float or dye methods are employed. Thus it may be useful to outline possible dye applications that would assist with this very real problem.

Certainly the addition of very small quantities of dye could assist with establishing if the squares cleared of vegetation and used for float determinations of surface velocity are in fact representative of the flow in the cross section. This would be a miniaturised version of the Jabiluka experiment described in section 4.
Given the extreme field difficulties of flow determination in the lower Magela dyes, would certainly have the potential to give information of times of travel. A line source, again similar to the Jabiluka experiment, upstream of a series of cleared areas could be used to establish time of travel through areas of thick vegetation. The sampling could also be undertaken at surface and depth to give information on vertical mixing. The sampling sites would be maintained for a sufficient period for the form of the dye concentration curve to be established and the relevant velocities calculated from the centroid of the dye distribution.

These suggestions are certainly not to be taken as true dilution gauging but used in conjunction with the float determinations may enable some independent check on the method.

It is worth commenting that dye dilution gauging methods have a considerable potential either for measuring very small flows, when standard current metering techniques are not applicable, or for gaining good estimates of extreme flows especially when the flow is over bankfull.

6.7 Dye Tracing and Modelling

The original field experiments in 1978 were undertaken, in part, to provide information as one of the inputs into hydrological and water quality modelling. The general approach is described in Goldberg (1978).

Linked to that approach is the use of mathematical and modelling techniques to extend the field information on dispersion. Although the dye tracing methods can yield useful information the size, and therefore the cost of field experiments, is such that every effort should be made to gain the maximum information from the results. Thus, wherever possible, the design of the field experiments should
be undertaken so that the results can be as fully extended by later modelling as is possible. This is certainly the case if the results are to be employed as an input into a possible management plan for the release of contaminated waters from uranium workings within the region.

6.8 Conclusion

It is hoped that the experience and results of the 1978 and 1979 experiments will be valuable in enabling the Water Division to use fluorometric methods for dispersion studies in the Magela Creek System. Suggestions for future work and sampling strategies have been outlined but for any specific application accumulated experience remains a major factor. For any major application it is strongly recommended that a reconnaissance experiment is carried out.

In putting forward additional hydrological applications in the soil and groundwater field it is stressed that these especially would need some prior experimentation before they were considered as any form of routine exercise. Only limited references to the literature have been quoted in this report but the authors would be most willing to extend these suggestions if requested.
LIST OF REFERENCES


Lewis, D.C., Kriz, G.J. and Burgy, R.H. 1966 Tracer dilution sampling techniques to determine hydraulic conductivity of fractured rock. Water Resources Res. 2(3), pp.533-542


### TABLE 2.1 VELOCITIES CALCULATED FOR VARIOUS SITES FOR THE 1979 EXPERIMENT

<table>
<thead>
<tr>
<th>SITE NUMBER</th>
<th>DISTANCE FROM INJECTION POINT (IN KM)</th>
<th>TIME FROM INJECTION TO FIRST ARRIVAL</th>
<th>VELOCITY IN KM/HR FROM INJECTION POINT</th>
<th>FIRST ARRIVAL</th>
<th>PEAK</th>
<th>CENTROID</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3.8</td>
<td>3 hrs</td>
<td>1.26</td>
<td>1.08</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9.0</td>
<td>6 hrs</td>
<td>1.50</td>
<td>1.26</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11.5</td>
<td>7 hrs 15 mins</td>
<td>1.59</td>
<td>1.33</td>
<td>1.27</td>
<td></td>
</tr>
<tr>
<td>Traverse 1</td>
<td>11.67</td>
<td>7 hrs 30 mins</td>
<td>1.53</td>
<td>1.22</td>
<td>1.04</td>
<td></td>
</tr>
<tr>
<td>Traverse 2</td>
<td>12.5</td>
<td>9 hrs</td>
<td>1.39</td>
<td>1.09</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>13.83</td>
<td>11 hrs</td>
<td>1.26</td>
<td>0.99</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>17.7</td>
<td>&gt; 24 hrs</td>
<td>E 0.81</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>19.4</td>
<td>28 hrs</td>
<td>E 0.69</td>
<td>E 0.40</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Traverse 4/Site 7</td>
<td>20.1</td>
<td>38 hrs</td>
<td>E 0.53</td>
<td>E 0.39</td>
<td>E 0.26</td>
<td></td>
</tr>
<tr>
<td>Traverse 5</td>
<td>21.1</td>
<td>38 hrs</td>
<td>E 0.55</td>
<td>E 0.36</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Traverse 6</td>
<td>22.5</td>
<td>60 hrs</td>
<td>0.38</td>
<td>E 0.27</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Traverse 7</td>
<td>25.0</td>
<td>75 hrs</td>
<td>0.33</td>
<td>E 0.27</td>
<td>-</td>
<td></td>
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E = Estimate
### TABLE 2.2 A COMPARISON OF VELOCITIES FOR THE EXPERIMENTS OF 1978 AND 1979

<table>
<thead>
<tr>
<th>SITE NO</th>
<th>DISTANCE FROM INJECTION POINT (IN KMS)</th>
<th>TIME TO FIRST ARRIVAL</th>
<th>VELOCITY FIRST ARRIVAL IN KMS/HR</th>
<th>VELOCITY CALCULATED FROM CENTROID IN KMS/HR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
<td>3 hrs</td>
<td>3 hrs</td>
<td>1.26</td>
</tr>
<tr>
<td>Traverse 1</td>
<td>3 Station 0</td>
<td>11.5</td>
<td>8.5 hrs</td>
<td>7.5 hrs</td>
</tr>
<tr>
<td>Traverse 2</td>
<td>4</td>
<td>12.5</td>
<td>10.0 hrs</td>
<td>9.0 hrs</td>
</tr>
<tr>
<td>Traverse 3</td>
<td>5</td>
<td>17.7</td>
<td>E 31 hrs</td>
<td>E 22 hrs</td>
</tr>
<tr>
<td>Traverse 4</td>
<td>6</td>
<td>19.4</td>
<td>30 hrs</td>
<td>28 hrs</td>
</tr>
<tr>
<td>Traverse 5</td>
<td>Traverse 1</td>
<td>21.1</td>
<td>5 days</td>
<td>38 hrs</td>
</tr>
<tr>
<td>Traverse 6</td>
<td>Traverse 2</td>
<td>22.5</td>
<td>6 days</td>
<td>60 hrs</td>
</tr>
<tr>
<td>Traverse 7</td>
<td>Traverse 3</td>
<td>25.0</td>
<td>7 days</td>
<td>75 hrs</td>
</tr>
</tbody>
</table>

E = Estimate
Fig 3: Selection of time-series plots for Traverse 1.
Fig 2.8 Contoured plots, Traverse 2

Traverse 2

Depth in metres

West

1

2

3

4

5

6

7

East

0.05

0.12

0.48

0.58

0.67

0.55

0.40

0.20

0.06

0.09

0.28

0.48

0.54

0.30

a.1

1855-1920 13 Feb
Gauge -

2000-2030 Feb 13
Gauge -

2100-2125 Feb 13
Gauge 9.750 m.

0200-0220 Feb 14
Gauge 9.800 m.

1.3

1.1

1.2

1.47

1.52

1.53

1.52

1.44

1.2

1.21

1.22

1.47

1.5

1.3

1.4

1.24

1.35

0.8
Fig. 2.9 Selection of time-series plots for Traverse 2
Traverse 1

Station 2
- Surface
- Depth

Fig. 2.10a. Surface and depth concentrations for Station 2, Traverse 1
Fig. 2.10b. Surface and depth concentrations for Station 7, Traverse 1.
Fig. 2.10c. Surface and depth concentrations for Station 2, Traverse 2.

Fig. 2.10d. Surface and depth concentrations for Station 6, Traverse 2.
Fig. 2.12  Dye concentration, Site 5

Fig. 2.13  Dye concentration, Site 6
Fig. 2.14 Dye concentration, at GS821023
Fig. 2.15 Dye concentrations, surface at Traverse 3

Traverse 3
- 1100 14-Feb.
○ 1600 14-Feb.
● 1100 15-Feb.
△ 0930 16-Feb.
+ 1400 17-Feb.
Fig. 2.16. Surface and depth concentrations selected stations, Traverse 3

Traverse 3

Surface

Depth

Dye concentration in µg/l

East

Station Numbers

West

0

0.2

0.4

0.6

0.8

1.0

1.2

1.4

1.6

0

1

2

3

4

5

6

7

8

9

10

1130 Feb 14

1600 Feb 14
Fig. 2.17 Dye concentrations, Site 7

- X Site 7
- O Values for Site 7 on Traverse 4
Fig. 2.18 Dye concentrations, Traverse 4

Traverse 4

1330 Feb. 20

1400 Feb. 19

1530 Feb. 18

1330 Feb. 17

1330 Feb. 16

1100 Feb. 15

0900 Feb. 14

Dye concentrations in % out
Fig. 2.20 Dye concentration, Site 8

Fig. 2.21 Dye concentration, Site 9.
Fig. 2.22a. Dye concentration, Traverse 5
(Feb 15-Feb 17)

- 0900 Feb 17
- 1900 Feb 16
- 0900 Feb 16
- 1640 Feb 15
- 0830 Feb 15

West
East
Fig. 2.22b. Dye concentration

Traverse 5 (cont)
(Feb 17 - Feb 20)

0730 Feb 20

0800 Feb 19

0900 Feb 18

1900 Feb 17

Dye concentration
µg/L

West

East
Fig 2.23 Dye concentration, Traverse 6

Traverse 6

- 0930 Feb 19
- 0730 Feb 20

0930 Feb 18

0930 Feb 17

1830 Feb 16

- 0930 Feb 16
- 1700 Feb 15
- 0900 Feb 15
Fig 2.24: Dye concentration Traverse 7

Traverse 7

0900 Feb 19

1000 Feb 18

1830 Feb 17

× 1800 Feb 16
○ 1100 Feb 17

1000 Feb 16

1000 Feb 15

West

East
Fig 2.25 Dye concentration, autosampler Traverse 6

Autosampler - Traverse 6
Fig. 2.26 Time-series concentration plots for Traverses 5, 6 & 7

Traverse 5
- Right Bank
- Left

Traverse 6
- Right Bank
- Left

Traverse 7
- Right Bank
- Centre
- Left

15 16 17 18 19 20 Feb.
Fig 2.27 Discharge Record at GS 821 009 (Site 1)

Discharge in Cumecs
FLOW AT MUDGINBERRI

Discharge at Mudginberri

Fig. 2.28 Discharge at Mudginberri

Temperature & Dye concentration
Hidden Billabong

Fig. 2.29 Temperature & Dye concentration
Hidden Billabong
Fig. 3.1 Sketch Map of Galungul Experiment
Fig. 32 Sampling Sites and Depths
Gulungul Billabong

Approx. Scale

0 250m

Thick aquatic growth

Gauge

1.8m

2

2.1m

3 (2.1m)

4 (1.2m)

5 (2.1m)

6 (2.4m)

7 (0.8m)

8 (1.1m)

9 (1.1m)

10 (1.0m)

11 (0.7m)
Fig 3.3 Dye concentration at Station 1

- Manual Sample
- Auto Sample

Fig 3.4 Dye concentration at Station 2

Time in hours
Fig. 3.5 Surface dye concentrations for Gulungul area.
Fig. 3.6 Dye concentration at Site 8

- Halo sample
- Manual sample

Dye Concentration in ng/Litre

Background Concentration
Fig 4.1 Location Map of Sampling Sites
Jabiluka Billabong

Approx. Scale
0 - 500m

Major flow lines
Open water
<table>
<thead>
<tr>
<th>East</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>West</th>
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<tbody>
<tr>
<td>S</td>
<td>.04</td>
<td>.04</td>
<td>5.20</td>
<td>2.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.0m</td>
<td>.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2.0m</td>
<td>.06</td>
<td>4.20</td>
<td>2.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>3.0m</td>
<td>.60</td>
<td>4.90</td>
<td>2.20</td>
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<td></td>
</tr>
<tr>
<td>T</td>
<td>4.0m</td>
<td>.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>H</td>
<td>5.0m</td>
<td>1.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.6m</td>
<td>0.15</td>
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</table>

**Traverse A 1126-1159**

<table>
<thead>
<tr>
<th>East</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>West</th>
</tr>
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<tbody>
<tr>
<td>S</td>
<td>.25</td>
<td>.29</td>
<td>.05</td>
<td>1.70</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1.0m</td>
<td>.23</td>
<td>.20</td>
<td>1.50</td>
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**Traverse A 1206-1225**

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**Traverse B 1228-1241**

All concentration values in µg/L.

**FIGURE 4.2.** Dye concentration values for Stations 1-5, Traverses A, B, and C, in the open water section of Jabiluka Billabong.
Fig 4-3 Depth-concentration Relationships Jabiluka Billabong

Traverse A
- 1145 hrs.
- 1215 hrs.

Traverse B
- 1400 hrs.
- 1230 hrs.

Traverse C
- 1430 hrs.
- 1300 hrs.
Fig. 5.1 Relation of Tritium to Dye.

Fig. 5.2 Relation of Tritium to Dye, low values only.
Fig. 5.4 Relationship of rhodamine and tritium concentrations to time.

- Feb 16 3 days *
- Feb 17 4 days *
- Feb 18 5 days *
- Feb 19 6 days *

Fig. 5.5 Dye and tritium concentrations for Site 4.

- Dye
- Tritium
Fig. 5.6  Dye and tritium concentrations for Traverse 6.

Tritium, bars show standard deviation.
Fig. 5.7  Dye and tritium concentrations for Traverse 4.
APPENDIX 1

Modelling Dispersion

1. Introduction

When a soluble tracer, or a pollutant, is injected into a naturally flowing river then the substance will travel downstream with the water flow. As the substance mixes across the cross-section of the river it encounters different velocities of flow in different parts of the river cross section. In general, the central parts of the surface water move fastest and the water near the bottom and the banks slowest. The tracer in the slow moving regions lags behind that of the faster flowing sections and there is a spread in the longitudinal direction.

This longitudinal spread of material was studied by Taylor (1953) who postulated that the combined effects of convection and diffusion could be represented as a one-dimensional Fickian type of diffusion. This process was called dispersion, in order to avoid confusion with molecular or turbulent diffusion. For a conservative tracer it is mathematically described by a second order partial differential diffusion equation of the form

\[
\frac{\partial c}{\partial t} = -U \frac{\partial c}{\partial x} + D \frac{\partial^2 c}{\partial x^2}
\]  

(1)

where \(x\) is the longitudinal distance, \(t\) is time, \(c\) is the concentration of material, \(U\) represents velocity and \(D\) is a coefficient of dispersion.

If there is an initial impulse (i.e. an instantaneous input) of \(M\) kg. of tracer material at \(x = 0\), \(t = 0\) then the resulting solution of (1) is in the form
\[
c = \frac{M}{2A\sqrt{\pi Dt}} \exp \left\{ -(x^* - Ut^*)^2 / 4Dt^* \right\}
\]

where \( x^* = x - x_0 \), \( t^* = t - t_0 \) and \( A \) is the cross-sectional area of the river. The constants \( x_0 \) and \( t_0 \) are usually set equal to zero, though this is formally valid only for large values of \( x \) and \( t \) (Holley and Tsai, 1977).

The constants \( U \) and \( D \) are determined from experimental data by taking moments of the curve of concentration \( c \) against time \( t \). At a downstream distance \( L \) from the injection point:

\[
U = \frac{L}{\bar{t}}
\]
\[
D = \frac{\sigma^2 U^3}{2L}
\]

where \( \bar{t} = \int_0^\infty c \, t \, dt / \int_0^\infty c \, dt \) is the centroid time of travel and

\[
\sigma^2 = \int_0^\infty c(t - \bar{t})^2 \, dt / \int_0^\infty c \, dt
\]

\[
= (\int_0^\infty c t^2 \, dt / \int_0^\infty c \, dt) - \bar{t}^2
\]

is the variance of the concentration-time curve.

An alternative modelling approach is available by using a lumped parameter differential equation model which defines concentrations at selected points on the river. (Buffham and Gibilaro, 1970; Whitehead and Young, 1975). This model is equivalent to solving a set of \( N \) input-output mass conservation equations of the form:

\[
\frac{L}{N} \frac{dc}{dt} = -uc + ub
\]

where \( c \) is the output concentration, i.e. the concentration in one of the \( N \) cells into which the length of river is divided, and \( b \) is the input concentration, i.e. the concentration in the previous upstream cell.
2. Finite Difference Modelling (Young and Beck, 1974)

Under normal field conditions, when a tracer experiment is conducted, the sampling of the tracer will be undertaken at a finite number of fixed sites. If we consider the observations at an upstream site to be \( b_{t-\Delta t}, b_t, b_{t+\Delta t} \) and the observations at the next downstream site to be \( c_{t-\Delta t}, c_t, c_{t+\Delta t} \) ... then an extended version of the finite difference form of equation (7) is

\[
c_t = \alpha c_{t-\Delta t} + \beta b_{t-k\Delta t}
\]

(8)

Figure 1 plots the results when equation (8) is used to model the flow of a tracer down a river when \( \Delta t = 1, k = 2, \alpha = 0.42, \beta = 0.4 \) and a pulse input of 100 units occurs at \( t = 0 \). At each observation point the calculated value of \( c_t \) becomes the input value of \( b_t \) for the next sampling point. It has been observed previously that the curves bear a definite qualitative and quantitative similarity to dispersion results obtained in real rivers e.g. Figure 4 of Day (1975).

The kinematics of the flow are principally determined by the parameter \( \alpha \) and by the lag \( k \). The parameter \( \beta \) provides a measure of the conservative nature of the tracer, or pollutant. For a conservative substance, such as salt or Rhodamine WT dye, one would expect the steady state gain of the system described by equation (8) to be unity, and hence \( \beta/(1-\alpha) = 1 \). If a certain fraction, say \( \gamma \), of a pollutant is lost by absorption or sedimentation then one would expect \( \beta/(1-\alpha) = 1 - \gamma \). Experimental situations do occur in which the steady state gain of a known conservative substance differs appreciably from unity. (Table 1). This occurs when there is poor or uneven mixing over the river cross section.
3. Theory

Let us imagine a unit impulse applied at \( t = 0 \) to the system

\[
c'_t = a c'_{t-1} + b b_{t-k}
\]

which is composed of equal length reaches extending downstream.

The concentration, \( c'_t \), at the reach \( (j+1) \) downstream from the injection point \( (j = 0, 1, 2, \ldots) \) is given in terms of combinatorials as

\[
c'_t = (t - j k - k) c_j p^j + l a t - j k - k
\]

Using the properties of combinatorials it may be shown that

\[
\Sigma c'_t = \frac{a^{j+1}}{(1-a)^{j+1}}
\]

\[
\Sigma t c'_t = \frac{(j+1) a^{j+2} (k - a k + \alpha)}{(1-a)^{j+2}}
\]

\[
\Sigma t^2 c'_t = (j+1) \frac{(j+2)}{(1-a)^{j+3}}
\]

\[
+ \frac{j k + k - j - 2 + (k - a k + \alpha) (j k + k - j - 1)}{(1-a)^{j+2}}
\]

hence

\[
\bar{c} = \frac{\Sigma c'_t}{\Sigma c'_t} = \frac{(j+1)}{(1-a)(k - a k + \alpha)}/(1 - \alpha)
\]

\[
\sigma^2 = \frac{(\Sigma t^2 c'_t/\Sigma c'_t) - \bar{c}^2}{(1-a)^2} = \frac{a(j+1)}{(1-a)^2}
\]

whence substitution into equation (3) and (4) for a distance of \((j+1)L\) gives the results of (9) and (10) below.

4. Comparison with Standard Modelling

The finite difference model of equation (8) may be compared to the Fickian diffusion model by taking moments of the concentration as it proceeds downstream. The results of this (see section 3) give
where $L$ is the length of the reach and represents the distance between the site at which $b_t$ is sampled and the site at which $c_t$ is measured.

The description of the tracer characteristics as they propagate downstream can now be reduced to the problem of estimating the parameters $\alpha$ and $k$ from data obtained on actual rivers, and comparing the results of (9) and (10) with the results of (5) and (6). This will be done in the next section.

Martin and Stokes (1979) have shown that the lumped parameter model of equation (7) is equivalent to a dispersion coefficient

$$D = \frac{UL}{2N}$$

which appears to offer a method for the determination of $N$ in equation (7), by equating the results of (9), (10), and (11).

5. Dye Dilution Gauging Results

The finite difference model of equation (8) was tested by using data obtained from a dye dilution gauging experiment conducted in the Magela Creek of the Northern Territory of Australia. A 10 kg. dry weight gulp of Rhodamine WT was released at the injection point (see figure 2.1) at 1030LT on February 13, 1979 and it was sampled for a downstream distance of 22km over a one week interval.

The finite difference model was applied to those parts of the Magela Creek data that were available in time series form. We chose data from sites 1, 2, 3, station 3 of traverse 1 and 2, as well as sites 4 and 5. During the course of the experiment an autosampler was set up towards the western side of traverse 6, and the results from this autosampler were also used. A graphic
representation of all of the dye data over the whole course of the experiment is given by using log-log coordinates, as in Figure 2; though the data from Traverse 1 have been omitted in order to avoid cluttering the diagram.

The \( \alpha \) and \( \beta \) parameters characterising each pair of sites were estimated by using the instrumental variable method detailed by Young (1974) and Young et al. (1978) and the results for various possible models are tabulated in Table 1. For comparison, the results obtained from the method of moments (equations 5 and 6) is given in Table 2, where the integrals are replaced by summation over the data set. Further comparison can be made with the least squares technique described in section 7 of this Appendix.

For some of the reaches listed in Table 1 there are a number of possible models that seem to provide an adequate representation of the data. As a general rule the model with the lowest value of the estimation error variance \( \text{norm} \) (the evn, Young, et al., 1978) is preferred. However when the model is based on a relatively small number of data points (say less than thirty) as is the case with the results of Table 1 then the choice of best model would be based on a joint appraisal of the evn and the correlation coefficient, \( R \), between the model's predicted result and the actual result. In addition the results of the moment method of Table 2 would provide a further basis on which to determine the best model.

6. Discussion

i) Site 0 (injection point) to Site 1

The high value of the evn for the model describing flow from the injection point to site 1 indicates that a simple first order version of (8) is not satisfactory over the initial 3.8km reach. (One should note the use of this data based method of validating the initial choice of model). A possible reason
for this is suggested by Holley and Tsai's (1977) work. For a
certain period of time after the dye injection - denoted the
initial convective period - the diffusion coefficient is not a
constant. (i.e. the variance of the concentration vs. time graph
is not linear). The diffusion coefficient seems to start at a
small value and gradually increases until it reaches a constant
value. Various workers have tried to find a non-dimensionalisation
that will provide a universal value for this initial convective
period, and hence provide a reach length over which the initial
convexion takes place but their results do not agree well with
field experiments (Day, 1975; Holley and Tsai, 1977). On the basis
of our result for the Magela Creek the initial convection appears
to take place over a 3 to 4 km reach length. It is of interest
to note that the results of Whitehead et al. (1978) indicate that
the Murrumbidgee River also has an initial convective length of
about 3km; and that the results of Day (1975), who found that the
variance of his concentration curves increased as the square of
the distance from the injection point, seem to also indicate that
a reach length of 2.25km is shorter than the initial convective
length.

Let us assume that the river from the injection point (site 0)
to site 1 can be modelled by two reaches:

\[ w_t = Aw_{t-\Delta t} + B d_{t-K\Delta t} \]

Reach 1

\[ c_t = \alpha c_{t-\Delta t} + \beta w_{t-k\Delta t} \]

Reach 2

then we find

\[ c_t = (A + \alpha) c_{t-\Delta t} - A c_{t-2\Delta t} + B d_{t-(k + K)\Delta t} \] (12)

The instrumental variable algorithm was used to estimate a
model of the form (12), and the full data set (\( \Delta t = 0.1667 \) hr) was
used. This resulted in the model

$$c_t = 1.56 \Delta c_{t-\Delta t} - 0.65 \Delta c_{t-2\Delta t} + 0.14 \Delta d_{t-20\Delta t} + 0.13 \Delta d_{t-21\Delta t}$$

which had log evn = -2.85 and $R^2 = 0.988$.

This model appears satisfactory, and actually turns out to be preferable (i.e. it had a lower evn) to one that incorporated a $c_{t-3\Delta t}$ term. The standard errors on the parameters are $1.56 \pm 0.16$ and $-0.65 \pm 0.15$. The similarity between the two coefficients of the $d$ terms seems to indicate that $k + \kappa = 20.5$ would be an appropriate choice, i.e.

$$c_t = 1.56 \Delta c_{t-\Delta t} - 0.65 \Delta c_{t-2\Delta t} + 0.27 \Delta d_{t-20.5\Delta t} \quad (13)$$

The exact numerical value of 0.27 is irrelevant since the input was arbitrarily set at 100 units and it is for this reason that the $s$ value was omitted in Table 1.

Equation (13) implies that $A = a = 0.78$. If we assume that the velocity in each of the two reaches is the same then we further have that $k = \kappa = 10.25$ which produces a final velocity of 0.83 km/hr and a dispersion coefficient $D = 0.0665 \text{ km}^2/\text{hr}$ in each of the two reaches.

ii) Site 1 to Site 2

The results of Table 1 indicate that when modelling half-hourly data from Site 1 to Site 2 the model with the lowest log evn (-6.85) and the high $R^2$ seems to underestimate the velocity and overestimate the dispersion coefficient when compared to the results of the moment method. The $U$ and $D$ values obtained from the run with a log evn of -5.36 seem more compatible with those obtained by the moment method. (We should reiterate here that the moment method cannot give us a value for $D$ between Site 1
and Site 2. However since the $D$ value for Site 0 to 2 is much the same as the $D$ value for Site 0 to 1 in Table 2 it indicates that one could expect the same dispersion between Site 1 and 2 as between Site 0 and 1 where we have found $D$ to be $0.0665 \text{ km}^2/\text{hr}$.

This was confirmed when the data sample was increased by using the full set of ten minute data from both sites. The resulting model with $u = 1.47 \text{km/hr}$ and $D = 0.067 \text{ km}^2/\text{hr}$ is consistent with the moment method estimate of a (slightly) higher velocity and identical dispersion coefficient. In fact, based on the steady state gain value, $\frac{\eta}{1 - \alpha}$, it is not clear that the ten minute data is providing a significantly better model since one would expect the steady state gain of a conservative substance such as Rhodamine WT to be about unity (within experimental error). The steady state gain, based on the ten minute data, lies between 0.38 and 0.52 whereas the steady state gain based on the model with a log evn of $-6.85$ lies between 0.61 and 0.96 which accords more closely with expectations and also with the results obtained between subsequent sites.

The increase in velocity which is also evident in the moment calculations is due to the dye being overtaken by a flood wave initiated by heavy rainfall far upstream of the injection point.

iii) Site 2 to Site 3

The model between site 2 and site 3 is both satisfactory and unique. That is to say, its evn was so much lower than the evn of any other choice of $k$ that one had no hesitation in choosing it. The velocity value accords with that between sites 1 and 2 though the dispersion coefficient is very much greater. The results of the moment method indicate some increase in $D$ over this reach and the extra input from two significant tributaries (Gulungul and Corndoli) would be expected to increase the
mixing and hence raise the value of D.

Nevertheless the similarity between these results and those for sites 1 to 2 when half hour data was used raised the question as to whether an increase in sampling rate would give a better value for D. By interpolating the ten-minute data from site 2 it was possible to obtain a data set with $\Delta t = 15$ minutes, and in much the same way as between sites 1 and 2, the greater sampling rate raised the velocity estimate slightly and lowered the estimate for the dispersion coefficient - which still stayed higher than that obtained over the previous two reaches.

iv) Site 3 to Traverse 1.

The problems of model identification come to the fore when modelling the flow as it enters the first billabong. Site 3 is just upstream of the entrance to the billabong whereas Traverse 1 is just inside the billabong itself. We may note that the model with the lowest evn does not have the highest $R^2$, and vice versa.

The results of the moment approach offer no help in this instance for deciding between the two models, and the large discrepancy in the $D$ value seems to arise from the $U^3$ term of equation (4). The very low velocity over this short reach results in a very low estimated value for $D$, whereas the average velocity between the injection point and Traverse 1 is an order of magnitude greater, leading to a very great overestimate of the dispersion coefficient in that region.

In the absence of any strong reasons to the contrary, the model with the lowest evn would be chosen.

v) Traverse 1 to Traverse 2.

These two sites represent the centre of the upstream and downstream ends of Mudginberri billabong. The steady state gain of this system, $\varepsilon/(1 - \alpha)$ is 0.69 which is significantly lower than
the steady state gain elsewhere in the system. Based on visual observations during the dye experiment and on subsequent analysis of the dye distribution along the cross-section of Traverse 1 and Traverse 2 (see section 2.3.2) it was apparent that

1) the dye was not well mixed along the cross-section of Traverse 1 whereas it had mixed by the time it reached the cross-section of Traverse 2 and ii) there was a dead water zone on the east bank of the billabong. The steady state gain of 0.69 almost certainly represents the diffusion of dye into this dead water zone. The dye travelling on the western side of the river traverses the length of the billabong, but the dye that passes Traverse 1 (in the centre of the billabong cross-section) does not all arrive at Traverse 2 but approximately 1/3 of it moves into the dead water area.

It takes approximately two hours for a parcel of water entering the billabong at its southern end, to leave it at its northern end. If we assume that equal amounts of dye were coming in at Stations 1, 2 and 3 then 1/3 of the dye came in at Station 3 and of this 1/3 was caught in the back eddy of the billabong. Thus about 1/9th of the total input dye moves down the billabong, back up it and then presumably back down. This is consistent with the observations at Stations 6 and 7 of Traverse 1. These Stations had peak dye concentrations only slightly below the peak of Station 3, but the concentration in the tail of the distribution was consistently three times higher there than at Station 3. Even though the dye had flushed out of the west side it continued to linger in the east side of the billabong.
vi) Traverse 2 to Site 4

Site 4 represents the first sampling site in the large flood plain of the river system. It is particularly interesting to note that the results from Traverse 2 to Site 4 are rather similar to those within the Billabong.

vii) Site 4 to Site 5

In traversing this weed and forest choked flood plain the velocity of flow decreases. There appears to be a substantial loss of dye though this could result from poor mixing of the dye along the cross-section of the sampling site, which was at the extreme eastern end of the cross-section.

The non-integer value of $k$ occurs because of the time difference between sampling times. Even though $\Delta t$ was one hour in both cases, samples at Site 4 were taken on the hour whereas samples at Site 5 were taken on the half-hour.

viii) Site 5 to Traverse 6.

The results at Traverse 6, situated at the western end of the large flood plain indicate that neither the location nor the sampling frequency were adequate for this finite difference modelling approach.

7. Results from Fickian models.

Chatwin (1971) proposed a method of analysing dispersion data which transforms the data and plots it for different values of $A$ (the river cross-sectional area) until the transformed data lies on a straight line. The method assumes that the data can be adequately represented by equation (2) with $x_0^* = 0$ and $t_0^* = 0$

$$C = \frac{M}{2AV^2Dt} \exp \left[\frac{-(x-Ut)^2}{4Dt} \right] \quad (14)$$

However, it does not appear to have been previously noted that
if equation (14) is indeed an adequate representation then a plot of $t \log_e (c/v)$ against $t$ should be parabolic in shape:

$$t \log_e (c/v) = a_2 t^2 + a_1 t + a_0 \quad (15)$$

where

$$a_2 = -U^2/4D$$

$$a_1 = \frac{UL}{2D} + \ln \left( \frac{M}{2A+D} \right)$$

$$a_0 = -L^2/4D$$

in which case a parabolic least squares fit will give estimates of $a_0$, $a_1$ and $a_2$ which will then enable $A$, $U$ and $D$ to be calculated.

It transpires that a least squares fit to the data transformed as $t \log_e (c/v)$ does not provide satisfactory estimates of the physical parameters. Basically it turns out that equation (14) appears capable of fitting either the ascending limb of the concentration curve, or the peak of the curve, or the tail of the curve. Though equation (14) produces a qualitative curve of the correct general shape, it appears to be less satisfactory at a quantitative level. It appears that the heuristically most pleasing fits are obtained when a weighted parabolic least squares fit is used in which each transformed data point is weighted according to the cube of its concentration.

Weighted parabolic least squares analyses were applied to the data from the sites listed in Table 1 of this appendix. The results are depicted in Figures 3 to 10 and the numerical values given on the figures bear direct comparison with those given in Table 2, from which it can be seen that virtually any method will give an adequate value of $U$, but that the value obtained for $D$ may differ between methods. Nevertheless, the most significant differences occur at Traverse 1, where we already know that the dye was not well mixed.
Though the weighted parabolic least squares method cannot be recommended for routine data interpretation, its use is valuable when i) the data collection occurred at irregularly spaced time intervals so that finite difference modelling (which requires data collected at the same time at each station) cannot be used; and when ii) data sampling missed a significant portion of the concentration curve so that the method of moments cannot be used (e.g., the data at Traverse 6 seemed to have missed the peak, whereas the sampling at sites 2 and 3 was not continued sufficiently long to give the form of the tail).

Once again it is worth emphasising that this analysis also assumed that the dye concentration was well mixed across the channel cross section. Where this is not the case, such as at Traverse 1, then all methods will give results that need to be considered with caution. It is clear that a flow of 72 cumecs at site 3, 49 cumecs at Traverse 1 and 79 cumecs at Traverse 2 (the method of moments gave 58 cumecs at Traverse 1 and 84 cumecs at Traverse 2) is suspicious since there are no tributary inputs into Mudginberri Billabong. Both methods estimate the flow \( Q \) as the quotient of the mass of dye injected and the area under the concentration-time curve. Whereas the dividend (mass of dye) remains a constant, the divisor (area under the curve) varied between Traverse 1 and Traverse 2 for station 3. This confirms that the river was not well mixed along its cross section at Traverse 1 and hence the flow estimates obtained at Traverse 1 will be meaningless.

For comparison with Figure 7, the results of the finite difference modeling from Traverse 1 to Traverse 2 are given in Figure 11.
8. Conclusion

We have demonstrated that finite difference modelling of tracer concentration provides an adequate representation of the flow and dispersion characteristics of a river. Though it assumes, as does Taylor's (1954) analysis, that the velocity and dispersion coefficient are constants, the ability of the finite difference method to model short reaches allows it to be used in areas where these parameters are varying - such as the initial convective period, or areas of the river undergoing transitions from channel flow to flood plain flow.

The finite difference modelling of equation (8) appears to be potentially valuable in modelling pollutant behaviour for rivers with known flow characteristics. The $\beta$ term allows for the possibility of pollutant drop-out due to sedimentation whereas the form of (8), based on an input-output relationship, permits the effects of inputs other than just a pure impulse to be examined.

In those situations where finite difference modelling cannot be used (e.g. data points are not equally spaced in time) then the method of moments provides a useful tool. In those situations where neither method can be used then one will need to resort to the weighted parabolic least squares method for estimates of flow, velocity and dispersion.
REFERENCES


Young, P.C., and Beck, B., 1974. The modelling and control of water quality in a river system, Automatica, 10, 455-468.

### TABLE 1

<table>
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<th>Sites (S)</th>
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<th>( \beta )</th>
<th>( k )</th>
<th>( U ) (km/hr)</th>
<th>( D^2 ) (km/hr)</th>
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## Table 2

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CAPTIONS FOR FIGURES

Figure 1: Response of equation (8) to a pulse input at $t = 0$.

Figure 2: Results of dye injection on the Magela Creek plotted on a log-log-plot.

Figure 3: Weighted parabolic least squares results for Site 1.

Figure 4: Site 2.

Figure 5: Site 3.

Figure 6: Station 3 Traverse 1.

Figure 7: Station 3 Traverse 2.

Figure 8: Site 4.

Figure 9: Site 5.

Figure 10: Traverse 6 Left Bank.

Figure A11: Finite difference modelling results for Traverse 2, Station 3 when the input was data from Traverse 1, Station 3.
MAGELA CREEK SITE 1

Mean Velocity (M/S) = 0.2607
Dispersion Coefficient (M**2/S) = 6.1929
Discharge (M**3/S) = 26.8756
Centroid (Hrs) = 4.0483
Variance (Hrs**2) = 0.2710

Figure 3
MAGELA CREEK SITE 2

MEAN VELOCITY (M/S) = 0.3332
DISPERSION COEFFICIENT (M**2/S) = 11.8831
DISCHARGE (M**3/S) = 52.8965
CENTROID (HRS) = 7.5019
VARIANCE (HRS**2) = 0.4469
MAGEA CREEK SITE 3

- Mean Velocity (m/s) = 0.3558
- Dispersion Coefficient (m**2/s) = 23.8358
- Discharge (m**3/s) = 72.9473
- Centroid (hrs) = 6.9774
- Variance (hrs**2) = 0.9389
TRAVERE 1 STATION 3

MEAN VELOCITY (M/S) = 0.3178
DISPERSION COEFFICIENT (M**2/S) = 48.9031
DISCHARGE (M**3/S) = 49.5131
CENTROID (HRS) = 10.1976
VARIANCE (HRS**2) = 2.7417
TRAVEL 2 STATION 3

MEAN VELOCITY (M/S) = 0.2964
DISPERSION COEFFICIENT (M**2/S) = 49.5410
DISCHARGE (M**3/S) = 79.4139
CENTROID (HRS) = 11.7137
VARIANCE (HRS**2) = 3.6691
SITE 4

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<td>Discharge (m³/s)</td>
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<td>Centroid (hrs)</td>
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<tr>
<td>Variance (hrs²)</td>
<td>4.4739</td>
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</table>

**Figure 8**
SITE 5

MEAN VELOCITY (M/S) = 0.6093

DISPERSION COEFFICIENT (M**2/S) = 3494.80

DISCHARGE (M**3/S) = 289.2811

CENTROID (HRS) = 8.1805

VARIANCE (HRS**2) = 42.3569
TRAVERSE 6 LEFT BANK

- Mean Velocity (m/s) = 0.1494
- Dispersion Coefficient (m²/s) = 402.27
- Discharge (m³/s) = 71.8666
- Centroid (hrs) = 41.4781
- Variance (hrs²) = 4153.80

![Graph showing concentration over time for Traverse 6 Left Bank with data points and a trend line.](image-url)
TRaverse 2
StATION 3

• DATA POINTS

\[ c = 0.42 c_{t-1} + 0.40 b_{t-1} \]
APPENDIX 2

DYE DILUTION GAUGING

The techniques of field fluorometry were initially developed to provide methods suitable for river gauging. A detailed discussion of the method is given by Wilson (1968) who prepared the standard manual for the United States Geological Survey Water Supply Division.

The method described however, uses a continuous input of the tracer dye. The alternative method, used in the Magela Creek studies, differs in that the tracer is rapidly poured into the stream over a time period which can be regarded as an instantaneous injection. This is often referred to, in the gauging literature, as the 'gulp' method. Continuous input, as described by Wilson, is the better method in that the results are thought to be more accurate. Indeed, most workers consider that the continuous injection dye gauging is the most precise of all the available gauging techniques. However, the 'gulp' method is much less demanding on personnel and equipment and is considered to be the more appropriate to the field conditions in the area. The loss in precision in determining the discharge is likely to be small.

The 'gulp' method employed, and the calculation of discharge, is briefly described below.

1. A sampling site is selected downstream of the injection point. The site should be selected so that complete cross sectional mixing of the dye is attained. This form of mixing should not be confused with that discussed in the consideration of dispersion given in Appendix 1. It is difficult to give specific guidance as to the length of this mixing distance, which will depend on a variety of local factors, but distance of 2 km should be sufficient for the larger rivers in the area. For smaller streams, the distance from injection point to sampling site could be reduced.
The sampling site should be in a well-defined section of stream channel as remote from major tributaries as is possible. The technique is limited if cross sectional mixing is poor. For example, dye in the Magela Creek, in the main experiment discussed in this report, was well mixed before it reached Mudginberri Billabong, but circulation within parts of the Billabong is poor and would therefore be unsuitable for a sampling site. Similarly, Traverses 3, 4, 5, 6 and 7 are unsuitable as the channel is not well defined.

2. **Selection of the injection site**

   The initial mixing is aided if it is possible to inject the dye at a waterfall or fast flowing section of the river. If such sites are not available injection into the centre of a fast flowing channel is the best alternative.

3. **Background samples**

   Samples are collected from the chosen sampling site prior to the passage of the dye pulse to establish the values for background fluorescence.

4. **Sample collection**

   Samples should be collected with a time interval chosen so that the resulting curve of concentration against time is well defined. Again, it is difficult to give detailed instructions as the velocity and location of the sampling site, in relation to the injection site, will vary from experiment to experiment. However, every effort should be made to ensure that the sampling interval corresponding to the first arrival of the dye pulse enables the form of the
curve to be accurately determined. It is important that the tail of the dye pulse is also well defined, although the sampling interval can be lengthened considerably at that stage. For many experiments the use of automatic water samplers to further define the tail of the dye pulse is recommended. If the tail of the dye pulse is not adequately sampled, estimation procedures can be used to extrapolate the concentration curve.

5. Construction of a dye concentration - time curve

After analysis of the samples a curve of dye concentration against time is drawn which will be similar in general form to that illustrated below.

\[
\text{Dye concentration} \\
\text{Time}
\]

The discharge can then be found by substitution in the following equation:

\[
Q = \frac{N}{\int_{0}^{\infty} (C_a - C_b) \, dt}
\]

Where

- \( Q \) = the stream discharge
- \( C_a \) = Dye concentration at time \( t \)
- \( C_b \) = Background dye concentration
- \( N \) = Mass of dry weight dye injected
The term \( \int (C_a - C_b) \, dt \) is the shaded area under the dye concentration curve.

There remains the problem of determining the input mass of dye suitable for a given location. Some guidance can be obtained from Kilpatrick (1976). Care should be taken not to use excessive amounts of dye.

REFERENCES


### APPENDIX 3

**DETAILS OF SAMPLES ANALYSED FOR THEIR TRITIUM CONTENT**

The details of time of collection, locality, tritium concentration and standard deviation for the samples analysed by the RAEC are presented below. The corresponding values for dye concentration as determined by the CRES team are also given.

<table>
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<tr>
<th>Location</th>
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<th>Tritium Activity</th>
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<td>μg.l⁻¹</td>
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