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Division of Earth, Marine and Atmospheric Science
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Report to the

WATER RESEARCH COMMISSION

on

DILUTION STUDIES ON LARGE OFFSHORE PIPELINES

by

W A M Botes

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DILUTION STUDIES ON LARGE OFFSHORE PIPELINES

Prepared for

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Prepared by:

Division of Earth, Marine and Atmospheric Science and Technology, CSIR

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SCOPE

At present 13 marine outfall pipelines are in operation in South Africa, discharging domestic and industrial effluent to the offshore environment. The performance of some of these pipelines is checked annually by biological/chemical impact assessment on the marine environment.

In 1984, on behalf of the Water Research Commission (WRC), the CSIR conducted a full scale physical performance check on the Camps Bay pipeline by introducing a conservative tracer in the system and measuring the actual dilutions achieved in the sea. This experiment was successfully conducted, and provided a more exact performance evaluation for marine outfall schemes.

During 1991 the CSIR was commissioned by the WRC to conduct similar performance assessments on three pipelines in South Africa over a period of three years to prove that achievable initial dilutions compare favourably with the theoretical predictions to support biological/chemical impact assessments and to facilitate the design process of new pipelines.

The study team include the following CSIR staff members: W A M Botes, S Taljaard, F van Dulm, C Roux, H Jelbert and E Mabille. The report was compiled by Mr W A M Botes of the Coastal Engineering Programme of the Division of Earth, Marine and Atmospheric Science and Technology of the CSIR in Stellenbosch.

KS Russell

K S RUSSELL
PRODUCTS MANAGER:
COASTAL AND HYDRAULIC ENGINEERING

Stellenbosch
August 1994

EXECUTIVE SUMMARY

The aim of this investigation was to establish the comparability of actual achievable initial dilutions and the theoretically predicted dilutions for a variety of existing marine outfalls along the South African coastline. This was done in order to make recommendations regarding the applicability of the different theories/approaches being used for the design of outfalls in South Africa.

The total achievable dilution which can be expected at a distant location is the product of the initial dilution, secondary dilution, dilution due to the die-off of microbilogical organisms and the chemical/biological dispersion of non-conservative substances .The initial dilution is the dilution achieved by the entrainment of seawater at the periphery of the plume, which reduces the effluent concentrations, during the rise of the buoyant effluent from the diffuser to the surface of the sea. The subsequent transport of the effluent away from the surfacing effluent plume, referred to as the effluent 'boil', brings about further reduction of the effluent concentration. This process is generally referred to as secondary dilution, which is caused by turbulence, eddies and shears, causing further entrainment/mixing of the seawater. Together with the chemical and biological dispersion of non-conservative substances and the die-off or decay of certain organisms during the transport of the effluent (dilution due to decay), the initial dilution and the secondary dilutions determine the ultimate concentrations of pollutants and subsequent impact on the designated uses at any location away from the discharge point.

The three study areas, Richards Bay, Vlees Bay and Hout Bay, were chosen to represent typical coastal conditions and various types of deep sea outfalls in South Africa. These experiments were conducted in close cooperation with the 'owners' of the outfalls and contributed to a great extent to the understanding of the hydraulic performance of the outfalls which should facilitate the normal operational procedures. The field experiment at Hout Bay coincided with the commissioning of the entire new sewage system and together with designers and contractors, the system was commissioned with thorough understanding and verification of the hydraulic behaviour.

The same methodology was followed for the three outfalls. Rhodamine-B was pre-diluted and released at the headworks. Samples were taken at the headworks downstream of the release point, at the diffuser (by divers or by pipe to the sea-surface) and in the effluent 'boil' to determine the initial dilutions as well as the dilutions in the moving effluent field. Samples were taken from a larger survey vessel, equipped with an accurate electronic navigational system as well as from more mobile ski-boats. The growth of the effluent field was recorded by circumnavigation and at each location an attempt was made to take aerial photographs. From these field experiments it was found that the photographic recording of an effluent field is not representative due to the unpredictable weather conditions and high dilutions.

For the Richards Bay outfall, application of the stagnant uniform theory was not realistic (due to the dynamic conditions present on the day of the exercise) resulting in under-estimations (conservative) of greater than six times for dilutions on days when current velocities exceed 30 $cm\ s^{-1}$. However, for the moving water theory, embodied in a model from the Environmental Protection Agency (EPA-United States), the over estimation of the achievable dilutions is between 1,1 and 1,6 and is similar to the prediction according to Wright (1984). For the Water Research Centre (WRc -United Kingdom) approach the predicted dilutions for actual conditions compared extremely well with the measured conditions.

For the Vlees Bay outfall the predicted dilutions for actual conditions using the EPA (1985) model, Wright (1984) and WRc (1990), compared well with the measured dilutions. The ratios between measured and predicted dilutions were 0,7 to 1,2, 1,2 to 1,3 and 1,1 for the three approaches respectively.

The discharge from the Hout Bay outfall was subjected to a strong thermocline in the water column which meant that samples had to be collected by divers at the thermocline. Although it cannot be proven outright whether these samples were representative, the ratio of the measured and the predicted mean dilution is close to unity, that is 0,7 to 1,4 for the EPA (1985) model and 0,9 by using the Water Research Centre (WRc) (1990) approach according to Lee and Neville-Jones (1987).

Although surface dilutions were more than 12 times greater than the initial dilutions measured in the trapped 'boil' at a thermocline located at approximately 10 m below the surface, the plume was still visible. The transport of the mean effluent field (trapped) may also be completely different to the transport of the visible surface field, especially during strong wind conditions.

With regard to the statistical analysis of the data, previous prototype dilution tests (Toms and Botes, 1987) indicated that the concepts 'minimum' and 'average' dilutions could not be properly defined and determined for the prototype tests. Due to complicated sampling strategies and methods the representativeness of the statistical distributions of the measured dilutions were doubtful. A conservative approach was followed by assuming the 'average' dilution refers to the highest concentration that could be detected. With (a) the experience gained by Toms and Botes (1987), (b) the results obtained from the present series of field tests and (c) the approach followed by WRc (1990) (that is, to consider more statistical parameters such as 95 percentiles, mean and median values for a typical frequency distribution curve for achievable dilutions) a more realistic approach was followed for this project by comparing similar statistical parameters for the predicted and measured dilutions.

To apply a 'stagnant uniform' theory to a dynamic receiving environment is not a realistic approach as the under-estimation of dilutions will be more than six times if ambient current speeds exceed 30 $cm\ s^{-1}$, irrespective of the theory that is applied (refer to Richards Bay).

When taking the ambient conditions into account the predicted dilutions according to EPA (1985), Wright (1984) and WRc (1990) compared well with the measured dilutions, although the EPA (1985) model provides a slightly more conservative prediction when considering mean dilution values. Considering the simplicity of the technique, the approach followed by WRc (1990) compares extremely well with the prototype measurements.

Numerous theories and models are available to predict the initial dilutions which can be achieved when a buoyant effluent is discharged to sea via a deep sea outfall. The choice of the technique to be applied is to be decided by the design engineer and must be agreed upon by the client and the control authority, since it is not practical to utilize numerous techniques for each and every study or design. The essential issue is that the technique applied should be considered reliable and the engineer should be aware of the sensitivity of the prediction for the diversity to physical conditions off the South African coast. Confidence in the theoretical prediction can only be gained by comparing the predicted values to actual achievable dilutions under various physical conditions.

The three field experiments together with the field experiment conducted at Camps Bay in 1984 (Toms and Botes, 1984) were extremely valuable, not only for the researchers of this study, but for the entire engineering and scientific community involved in the design and assessment of sea outfalls and marine water quality in South Africa.

The more sophisticated techniques provide more accurate predictions. However, the more detailed the desired output is, the more detailed the input is that is required. Taking the diversity and complexity of the South African coastline into account, the acquisition of data required for model inputs is extremely expensive in terms of manpower, sophisticated equipment and operational expenses.

This study demonstrated that by using the fairly simple technique suggested by the WRc (1990), the overall predictions are as accurate as the prediction by more sophisticated methods. This does not mean that the more sophisticated models should be disregarded for specific applications where more details on the behaviour of a rising plume may be required. When extensive data sets are not available the simpler techniques can be applied with confidence, especially when followed up by a few field experiments to determine the actual achievable dilutions.

The main objective of this study was to determine the applicability and accuracy of the theories/approaches which are applied to predict the initial dilution which can be achieved from long sea outfalls for South African coastal conditions. The three field exercises provided sufficient information for a range of ambient conditions to confirm the confidence with which the available theories can be applied, taking into account the availibility of physical data (currents and stratification).

The moving effluent field, after the initial dilution process, was monitored to obtain an estimate of the achievable secondary dilutions. The recorded secondary dilutions were limited to approximately five times within 200 *m* from the 'boil' whereafter only an additional twofold dilution can be expected even as far as one kilometre away from the discharge location. The verification of the available techniques (analytical or numerical) which are used for the prediction of achievable secondary dilutions was not done, as this was not within the scope of this study.

Recommendation: It is strongly recommended that the available techniques, both analytical and numerical (models), be applied to the data available from these experiments in order to prove and gain similar confidence as for the prediction of initial dilutions. The ultimate concentrations at the target locations are controlled by (a) the hydraulic performance of the outfall for the achievement of the required initial dilutions (controlled process) and (b) by the physical transport and decay of non-conservative variables, for example microbial organisms, which is an uncontrolled process which depends on nature. It will be extremely useful if a number of field experiments can be conducted where the measurement of the physical dilutions are combined with the decay of microbial organisms as these two processes determine the ultimate location of the outfall site. Present studies on the decay of microbial organisms and the transport/dispersion of an effluent field are limited.

Sophisticated numerical models to simulate the transport of an effluent field, including the decay of microbial organisms, are available but need to be verified under actual South African conditions.

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GLOSSARY OF TERMS/SYMBOLS

b	=	buoyancy flux per unit length of diffuser
B	=	buoyancy flux
	=	$\left(\frac{\rho_{sea} - \rho_{eff}}{\rho_{sea}}\right) g \cdot q_p$
d_j	=	port diameter (internal) (m)
F_j	=	Froude number of the jet
		$u_j \,/\, \left(g \cdot \frac{\Delta\rho}{\rho sea} \quad d_j\right)^{\frac{1}{2}}$
F_a	=	Froude number (Roberts, 1977)
	=	$U_a{}^3 / b$
g	=	gravitational acceleration ($m\ s^{-2}$)
g^1	=	relative density parameter
		$g\left(\frac{\rho_a - \rho_{eff}}{\rho_a}\right)\ (ms^{-2})$
G	=	density gradient parameter
		$\frac{g}{\rho_{sb}} \cdot \frac{(\rho_{ss} - \rho_{sb})}{h}$
h	=	water depth (m)
L	=	length of the diffuser (m)
q_p	=	port flow ($m^3\ s^{-1}$)
Q	=	total flow into diffuser ($m^3\ s^{-1}$)
S_{av}	=	average dilution
	=	1,74 S_{min}

S_{min}	=	minimum dilution
u_j	=	jet exit velocity ($m\ s^{-1}$)
U_a	=	ambient current velocity ($m\ s^{-1}$)
U_a	=	ambient current velocity ($m\ s^{-1}$)
y	=	height above the jet exit where S_{min} is determined (m)
$\Delta\rho$	=	$\rho_{sea} - \rho_{eff}$
ρ_{sea}	=	density of surrounding seawater ($g\ ml^{-1}$)
ρ_{eff}	=	density of effluent ($g\ ml^{-1}$)
ρ_{sb}	=	density of sea water at sea bed ($g\ ml^{-1}$)
ρ_{ss}	=	density of sea water at surface ($g\ ml^{-1}$)
ρ_a	=	average density of water column ($g\ ml^{-1}$)

1. INTRODUCTION

The aim of this investigation was to establish the comparability of measured achievable initial dilutions and the theoretically predicted values for a variety of existing long offshore pipelines along the South African coast and, where appropriate, to make recommendations regarding the applicability of the different prediction techniques used for the design of future long ocean outfalls. The prediction of achievable dilutions is essential to assess the possible impact which the effluent, discharged to the ocean, may have on the water quality of the receiving waters and the subsequent designated beneficial uses for the area. This will also determine the ultimate design of the outfall system, i.e. the discharge location, depth of discharge, length of pipeline, diffuser design and discharge mechanisms.

The total achievable dilution which can be expected at a distant location is the product of the initial dilution, eddy dilution and dilution due to the die-off of non-conservative parameters such as microbiological organisms. The initial dilution is the dilution achieved by the entrainment of seawater, which reduces the effluent concentrations, during the rise of the buoyant effluent from the diffuser to the surface of the sea. The initial dilution can be 'designed' for a particular outfall and effluent. For an effectively designed sea outfall, the initial dilutions generally caused a reduction of more than 150 times that of the effluent concentrations. The subsequent transport of the effluent away from the surfacing effluent, referred to as the effluent 'boil', brings about further reduction of the effluent concentration. This process is generally referred to as secondary dilution, which is caused by turbulence, eddies and shears, causing further entrainment/mixing of the seawater. Together with the chemical and biological dispersion of non-conservative substances and the die-off or decay of certain organisms during the transport of the effluent (dilution due to decay), the initial dilution and the secondary dilutions determine the ultimate concentrations of pollutants and subsequent impact on the designated uses at any location away from the discharge point.

Mixing of an effluent in a non-uniform receiving medium (i.e. where significant currents and/or stratification in the water column exist) is a complicated process which cannot be predicted easily by analytical or numerical techniques due to assumptions and the availability of detailed physical data (currents and stratification through the water column for all conditions which may occur). However, in a stagnant uniform medium the achievable dilutions obtained during the discharge of a buoyant effluent can easily be calculated theoretically, because the dilutions are only related to the buoyancy of the effluent relative to that of the ambient medium and the discharge velocity. This, in turn, causes the effluent to rise through the ambient medium to the water's surface, entraining seawater along that way.

For design purposes, the stagnant uniform theories are presently used as a conservative first assessment in the design of marine outfalls along the South African coast. Since stagnant uniform conditions are virtually non-existent in the marine environment, dilutions predicted by these conservative theories are often unrealistic for certain coastal areas, resulting in under-estimations of achievable initial dilutions (Toms and Botes, 1987), which in turn, are used for the assessment of potential environmental impact. This may result in excessive costs in the construction of marine outfalls.

To investigate the validity of the initial dilution prediction techniques for stagnant unstratified sea conditions and to comment on the applicability of the stagnant water theory to ocean outfalls subject to South African sea conditions, preliminary field tests were conducted at the Camps Bay marine outfall in 1984. This was done by introducing a relatively conservative tracer (i.e. the absorption in the pipeline and breakdown within the time which the experiment is conducted is negligible) into the outfall (Toms and Botes, 1987). The Camps Bay pipeline was selected firstly for its close proximity to the CSIR in Stellenbosch; secondly because the area was sheltered from prevailing winds, a condition which is necessary for the design and refinement of these field experiments. Field experiments are necessary to obtain confidence in the theoretical prediction techniques for the diversity of the South African coastal conditions and to standardize techniques for measuring the actual achievable dilutions for outfalls.

In 1991 the CSIR (Ematek) was commissioned by the Water Research Commission to undertake the present study, aimed at applying further the techniques developed at Camps Bay to other marine outfalls along the South African coastline; a study which was to be undertaken over a period of three years. Three pipelines were selected to be representative not only of various outfall designs and effluent types, but also to take into account the diversity of the physical conditions along the South African coastline. The pipelines selected were (Figure 1a):

- Richards Bay marine outfall for buoyant effluent (A-line)
- Mossgas marine outfall at Vlees Bay
- Marine outfall at Hout Bay.

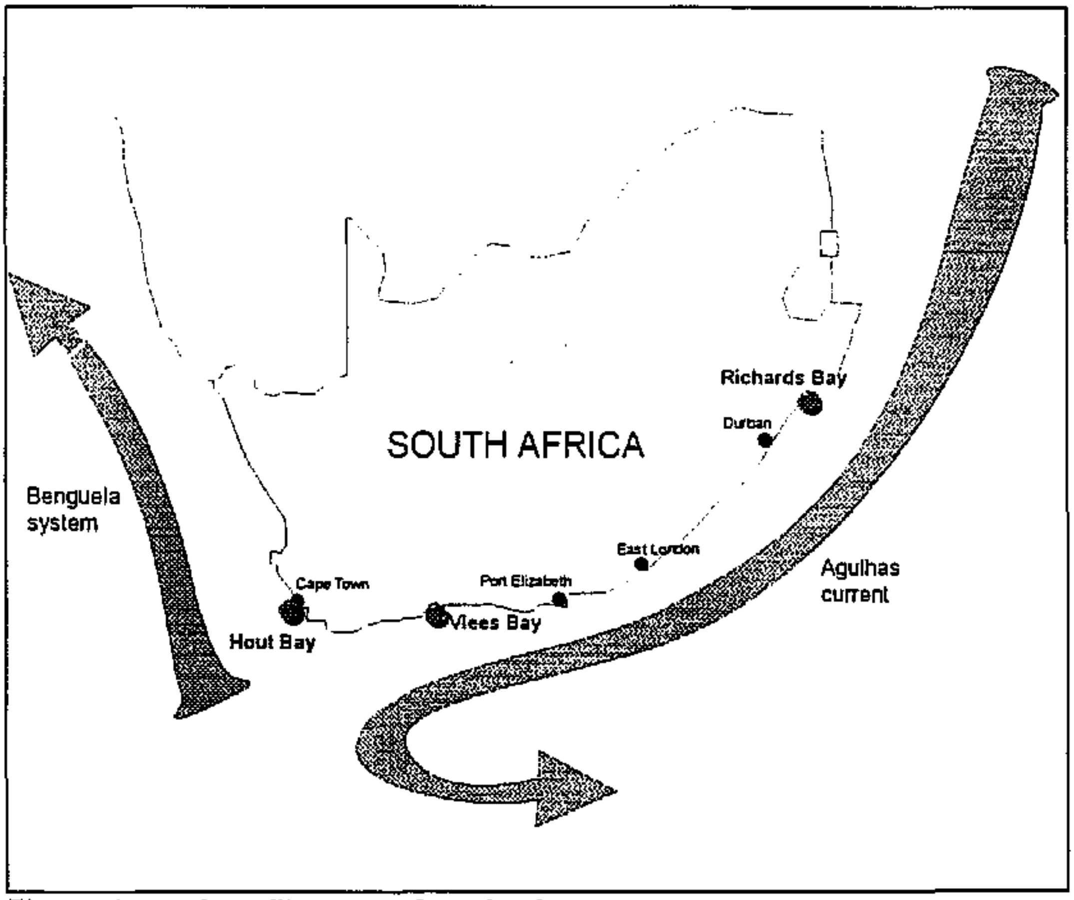

Figure 1a. Locality map of study sites

Results from this investigation are presented in this report, which is structured as follows:

Chapter 2: Description of the different study sites

Chapter 3: Description of theories and methodology applied in the study

Chapter 4: Results and discussion on the predicted (theoretical) and field (actual) dilutions obtained at each site, including a comparative assessment

Chapter 5: Conclusions and Recommendations.

2. STUDY SITES

2.1 Richards Bay Marine Outfall for Buoyant Effluent (A-line)

During 1980 two marine outfalls (A and B-line) were constructed at Richards Bay for the discharge of various industrial effluents and domestic sewage. The location of the outfalls are illustrated in Figure 1b. The entire outfall scheme is managed by the Mhlathuze Water.

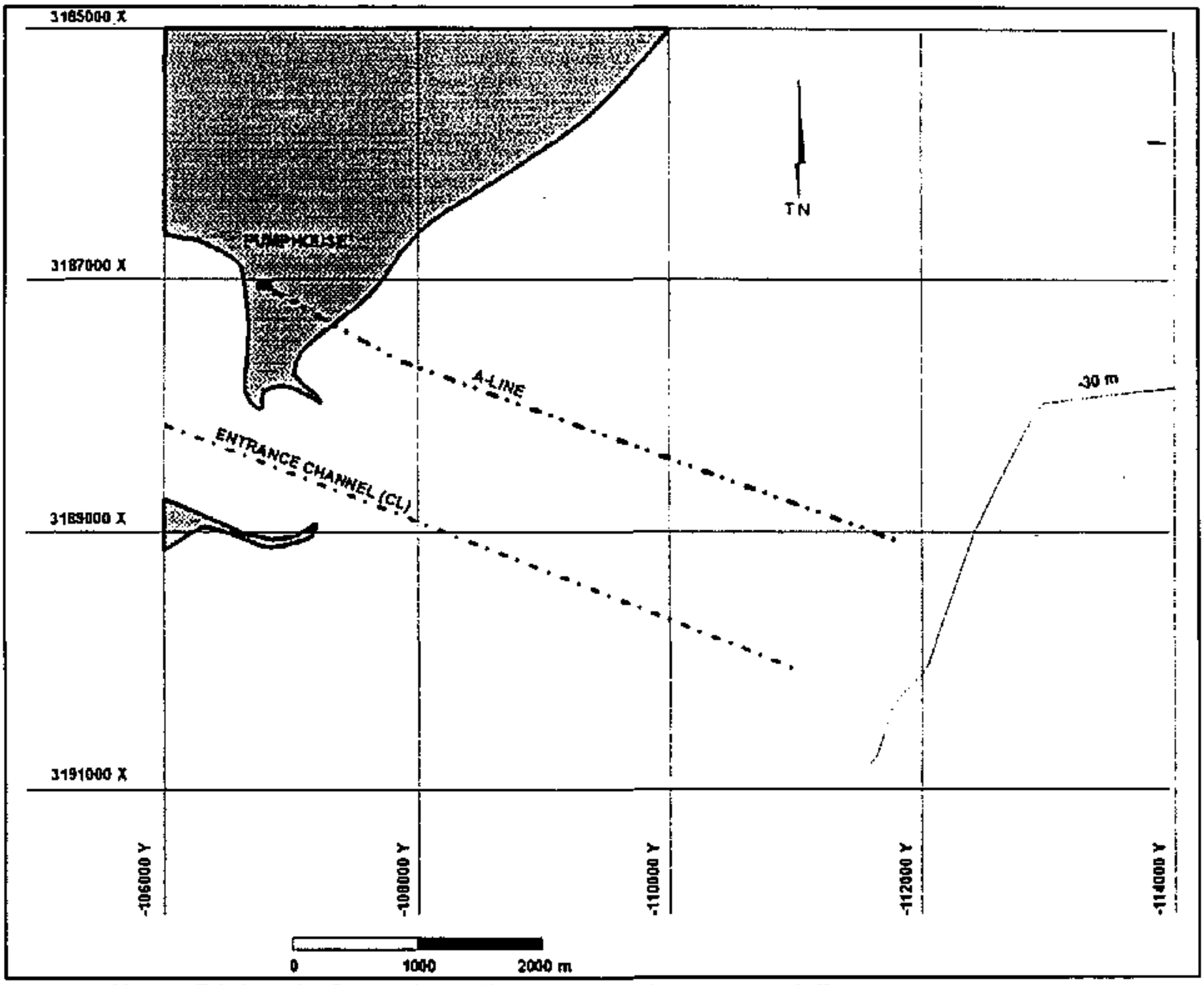

Figure 1b. Richards Bay: Locality map of the sea oufall

The A-line, which discharges in 29 *m* water depth approximately 4,8 *km* offshore, was designed to accommodate buoyant effluents from various industries and the domestic sewage from Richards Bay.

The B-line discharges in 24 *m* water depth and was designed for discharging 'dense' effluents from a fertilizer factory (presently owned by Indian Ocean Fertilizers).

According to DWAF (1991) the 1991 average total flow for the A-line was 1,15 $m^3\ s^{-1}$ and the average individual contributions to the buoyant flow pipeline (A-line) were:

Mondi Richards Bay:	85 310 $m^3\ day^{-1}$
Mondi Felixton:	7 034 $m^3\ day^{-1}$
Alusaf:	8 186 $m^3\ day^{-1}$
Borough of Richards Bay:	8 499 $m^3\ day^{-1}$ (domestic)
Indian Ocean Fertilizer:	895 $m^3\ day^{-1}$
TOTAL:	109 924 $m^3\ day^{-1}$

Due to an effluent flow of only 1,15 $m^3\ s^{-1}$, seawater is added to the effluent in order to discharge at the design flow rates of the outfall schemes. The average seawater intake during 1991 was 0,606 $m^3\ s^{-1}$, resulting in a total average flow to the sea of 1,7571 $m^3\ s^{-1}$ with an average density of 1003 $g\ l^{-1}$. These values represented the flows for a six months period in 1991 (DWAF, 1991). In 1991 the average effluent flow was only 60% of the design capacity which is the flow rate expected in the year 2020.

The main features and specifications of the Richards Bay marine outfall (A-line) which has been in operation since 1984 are:

- Effluent type: Industrial and domestic (bouyant in comparison with seawater)
- Discharge pattern: Continuous
- Material: HDPE (High density polyethylene)
- Pipeline length: 5 *km* offshore
- Water depth: 29 *m*
- Internal diameter: 920 *mm*
- Diffuser length: ~630 *m*
- Port configuration: 69 x 75 *mm* Ø, 6 x 115 *mm* Ø and 21 x 75 *mm* Ø
- Port spacing: 6,5 *m*
- Design flow rate: 160 000 $m^3\ day^{-1}$ (1,85 $m^3\ s^{-1}$)

The physical status of the diffuser in 1991 differed from the original design as follows:

- The sea-end of the diffuser was damaged by a ship anchor and subsequently shortened by ~ 60 *m* with a loss of ten 75 *mm* Ø ports. The end was blocked off.

- The diameter of port numbers 70 to 75 is 115 *mm* Ø instead of 75 *mm* Ø, resulting in increased flows and subsequent reduced dilutions through these ports.

- The discharge angles of the ports are vertical (twelve o'clock). The discharge angles of ten ports vary between ten and two o'clock orientation.

2.2 Mossgas pipeline at Vlees Bay

This ocean outfall at Vlees Bay, approximately 10 *km* west of Mossel Bay, was constructed in 1991 for discharging effluent from the Mossgas refinery. This outfall is owned and operated by Mossgas. The location of the outfall is illustrated in Figure 1c.

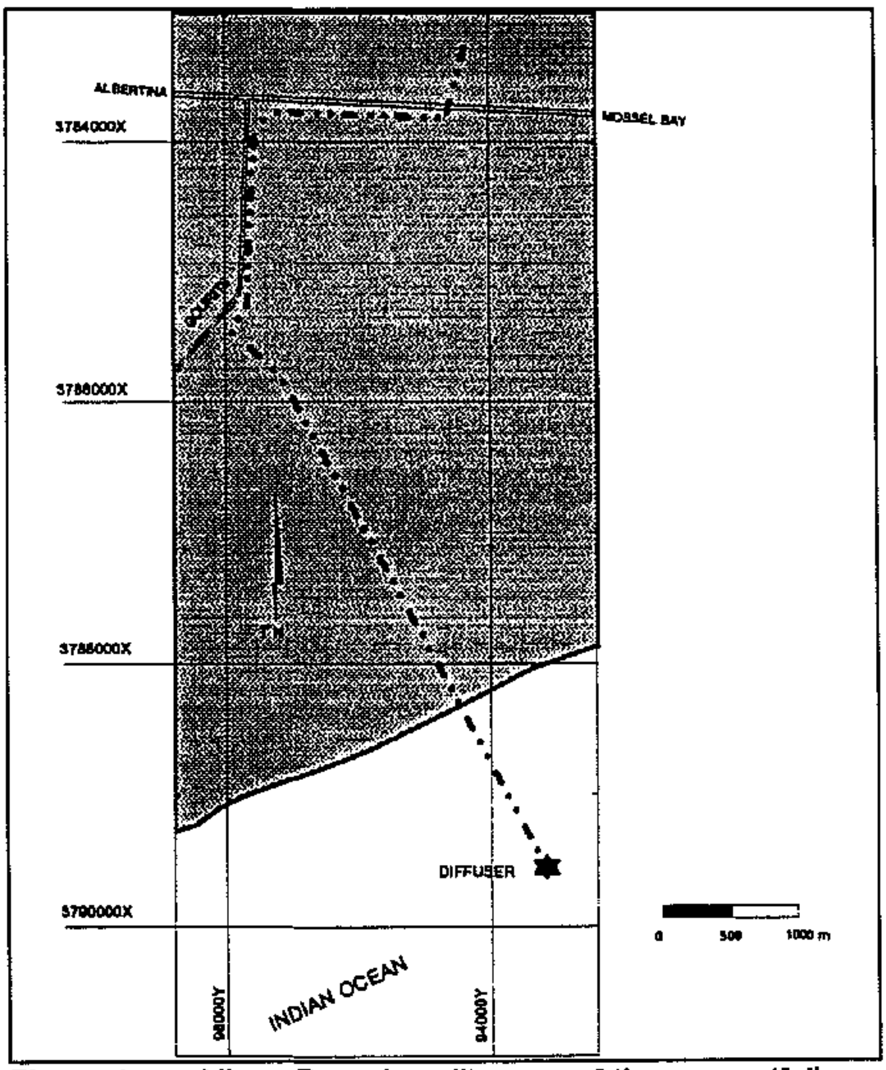

Figure 1c. Vlees Bay: Locality map of the sea outfall

The main features and specifications of the Mossgas pipeline at Vlees Bay which is in operation since 1992 are as follows:

- Effluent type: Industrial (bouyant)
- Discharge pattern: Intermittent
- Material: Steel
- Pipeline length: 9 *km* (refinery to diffuser)
  Diffuser is 1,4 *km* offshore
- Water depth: 27 *m*
- Internal diameter: 203,2 *mm*
- Diffuser length: 50 *m*
- Port configuration: 4 x 75 *mm* Ø and 1 x 79 *mm* Ø
- Port spacing: 3 x 10 and 1 x 8,5 *m*
- Design flow rates in phases: 0,052 $m^3\ s^{-1}$
  0,136 $m^3\ s^{-1}$
  0,167 $m^3 s^{-1}$

This outfall scheme is relatively new and from diving inspections the diffuser was in a good condition (as designed and constructed).

2.3 Marine Outfall at Hout Bay

The feasibility study for this marine outfall was completed in 1984 and the pipeline was commissioned at the time of this field exercise (6-12 October 1993). The pipeline is owned by the Western Cape Regional Services Council (WCRSC). The location of the outfall is shown in Figure 1d. The main pump station of the Hout Bay sewage scheme is situated at the Disa River with a rising main (2 460 *m*) to the treatment works. For discharging of the pre-treated effluent from the treatment works to the sea, the system operates on gravity flow but uses booster pumps when required.

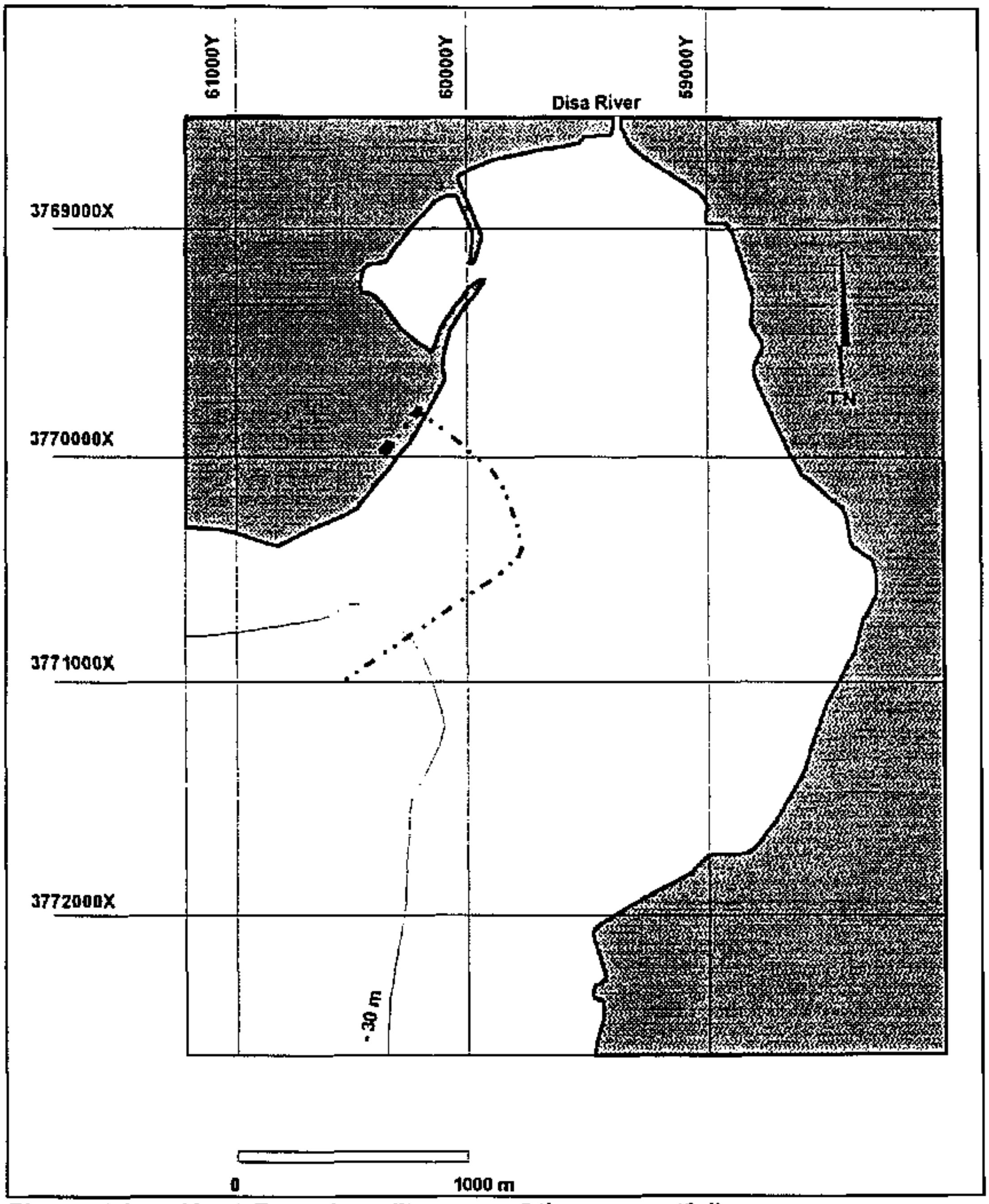

Figure 1d. Hout Bay: Locality map of the sea outfall

The marine outfall is designed to discharge between 120 and 130 $m^3\ s^{-1}$ by gravity. This is done intermittently when a valve at an outfall chamber opens automatically when the effluent reaches a certain level in a storage sump (25 m^3) at the treatment works. During higher flows two booster pumps provide the required head to discharge at a maximum rate of 202 $m^3\ s^{-1}$.

The main features and specifications of the marine outfall at Hout Bay which has been in operation since October 1993 are as follows:

- Effluent type: Domestic and industrial (Fishing industry)
- Pre-treatment: Maceration and fine screening
- Discharge pattern: Intermittent
- Material: High density polyethylene (HDPE)
- Pipeline length: 1,8 *km* offshore
- Water depth: 37 *m*
- Internal diameter: 364 *mm*
- Diffuser length: 114 *m*
- Port configuration: 10 x 110 *mm* Ø and 5 x 140 *mm* Ø
- Port spacing: 10 *m*
- Maximum design flow rate: 250 $m^3\ s^{-1}$
- Flow rate in 1993: 125 $m^3\ s^{-1}$

3. METHODOLOGY

3.1 Theoretical Dilution Predictions

With reference to Toms and Botes (1987) the theories of dilutions which were used in the theoretical prediction of dilutions can be summarized as follows:

3.1.1 Stagnant uniform theory

i. Roberts (1977)

This reference provides a useful review of the fundamentals involved in initial dilution prediction theory. Roberts shows by dimensionless analysis that the minimum dilution, S_{min}, in stagnant uniform sea conditions, on the centre line of a buoyant plume of effluent rising from a single round port in a diffuser on the sea bed depends on two dimensionless groupings:

$$\frac{S_{min}}{F_j} = \left(\frac{y}{d_j . F_j}, \frac{1}{F_j}\right) \quad (1)$$

where

	y	=	height above the jet exit where S_{min} is determined (*m*)
	d_j	=	port diameter (internal) (*m*)
	F_j	=	Froude number of the jet
		=	$u_j \,/\, \left(g \frac{\Delta\rho}{\rho sea} \; d_j\right)^{\frac{1}{2}}$
and	u_j	=	jet exit velocity ($m\ s^{-1}$)
	g	=	gravitational acceleration ($m\ s^{-2}$)
	$\Delta\rho$	=	$\rho_{sea} - \rho_{eff}$
	ρ_{sea}	=	density of surrounding seawater ($g\ ml^{-1}$)
	ρ_{eff}	=	density of effluent ($g\ ml^{-1}$)

Figure 2 illustrates the achievable centreline dilution of a round buoyant plume rising in stagnant uniform sea.

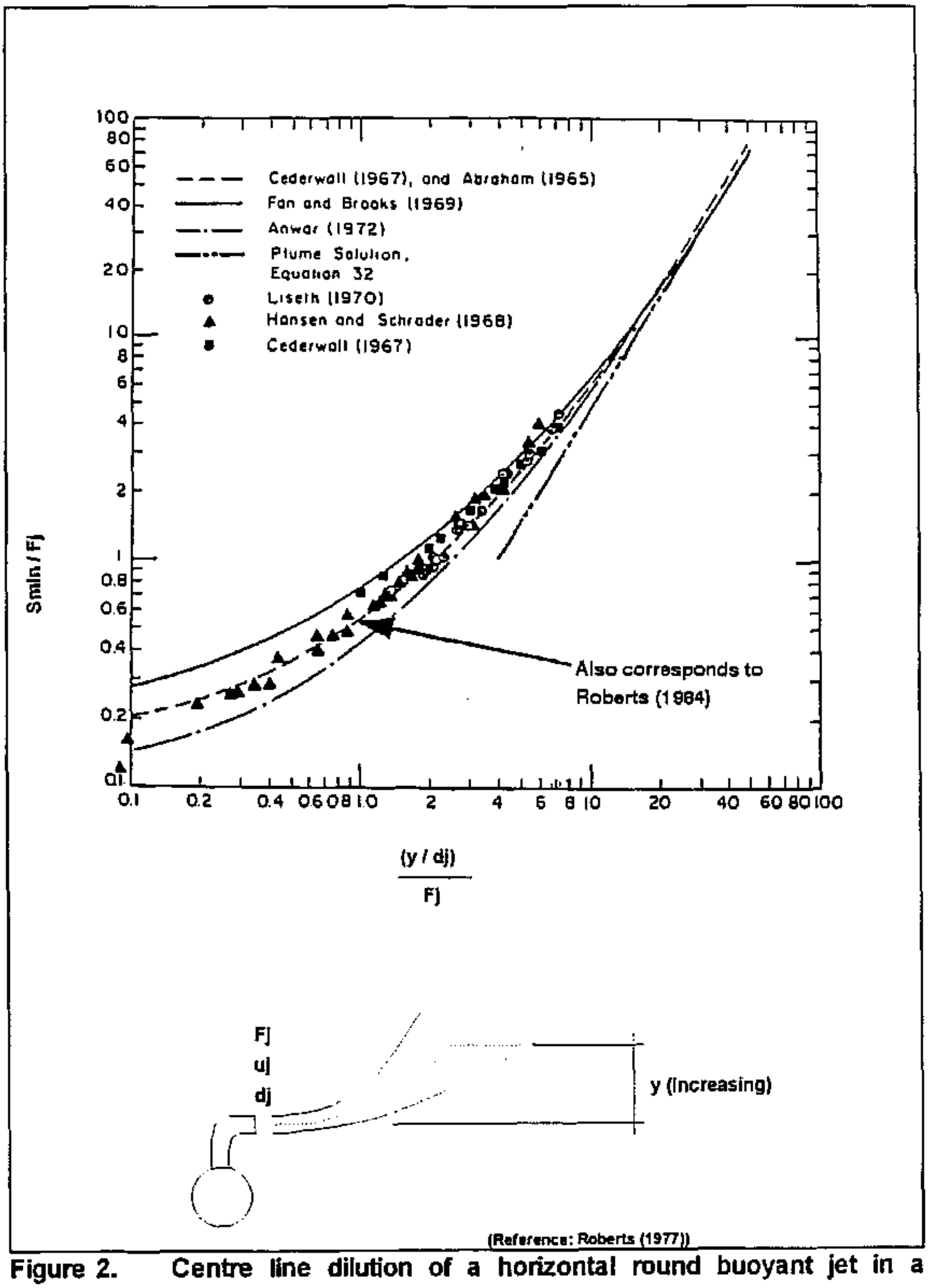

Figure 2. **Centre line dilution of a horizontal round buoyant jet in a stagnant uniform fluid**

Roberts (1977) summarizes initial dilution prediction methods (Cederwall, 1967; Abraham *et al.*, 1983; Fan and Brooks, 1969). Fan and Brooks (1969) developed theoretical procedures solving simultaneous differential expressions for conservation of continuity, momentum, density difference and concentration. These are solved by numerical integration. Roberts (1977) further compares these with laboratory experiments (Hansen and Schroder, 1968; Cederwall, 1967; Liseth, 1970). The 'plume solution', also shown in Figure 2, is valid only where the ratio (y/d_jF_j) is above 20. The following general equation, fitting the full curve, was proposed by Roberts (1984):

$$S_{min} = 0{,}107 . F_j (1{,}6 + 5 \left(\frac{y}{d_j . F_j}\right) + \left(\frac{y}{d_j . F_j}\right)^2)^{\frac{5}{6}} \qquad (2)$$

This is valid for all values of ($y/d_j.F_j$) and reduces to the 'plume solution' for high (>20) values as shown below:

$$S_{min} = 0{,}107 . F_j \left(\frac{y}{d_j . F_j}\right)^{\frac{5}{3}} \qquad (3)$$

The S_{min} relates to centre line dilution. The plume is assumed to have a Gaussian (bell-shaped) concentration distribution symmetrical about its centre line, and reference is more commonly made to S_{av}, the profile averaged dilution, where:

$$S_{av} = 1{,}74 . \ S_{min} \qquad (4)$$

For purposes of comparison, as required for this report, equations (2) and (4) provide the best estimate of theoretical initial dilution at a height y above the outlet in stagnant uniform conditions.

ii. *WRc (1990)*

After recent re-analysis of laboratory and field data the WRc (1990) suggested the following approach for horizontal round buoyant jets:

Two regimes for round buoyant jets should be considered: (a) the buoyant dominated near field (BDNF), when the buoyancy flux of the rising plume is the controlling parameter for achievable dilutions, and (b) the buoyancy dominated far field (BDFF), when the dilution is influenced less by buoyancy and more so by ambient currents.

In South Africa the terms *'initial dilution'* and *'far field dilution'* are commonly used, where *'far field dilution'* refers to secondary dilution and decay (in the case of microbial organisms). To prevent confusion, the terms *'buoyant dominated near field'* and *'buoyancy dominated far field'*, used by WRc (1990), will be referred to as a *'buoyancy dominated condition'* (BDC) and a *'current dominated condition'* (CDC), respectively, in this report.

For a discharge into cross-flowing currents the CDC exists when:

$$y < (5.B)/U_a^3$$

where:

where:	y	=	height above the port exit (*m*)
	U_a	=	ambient current velocity ($m\ s^{-1}$)
	B	=	buoyancy flux
		=	$\left(\frac{\rho_{sea} - \rho_{eff}}{\rho_{sea}}\right) g \cdot q_p$

For the BDC the achievable dilution at the water surface, S, is given by:

$$S = C\,(B^{1/3}.h^{5/3})/q_p$$

q_p = port flow ($m^3\ s^{-1}$)

Actual measurements of concentrations (dilutions) scattered considerably due to the complex mixing process in the receiving seawater. Statistical analysis of field data by WRc (1990) has provided values for C which correspond to different probabilities of exceedance for minimum initial dilutions. The C-values for a buoyancy dominated condition according to WRc (1990) are:

C = 0,16 for 95% (percentile) dilutions

C = 0,27 for median values (50%)

C = 0,34 for mean values (38%)

3.1.2 Moving water (non-uniform sea) theory

To evaluate the initial dilution, including the effects of ambient currents and vertical density gradients, theoretical computations become more complex. While a full description of the theories available and their development is beyond the scope of this report a brief description of three different approaches is given.

i. Roberts (1977)

In this approach laboratory testing was performed to provide empirically derived coefficients for relationships based mainly on dimensional analysis. The relationships in question relate to 'slot plumes' that are equivalent to a curtain of buoyant effluent rising in a homogeneous sea. Such a curtain would be formed by closely spaced diffusers, causing merging plumes close to the sea bed.

Roberts (1977) makes use of a dimensionless Froude Number, F_a, to describe the relative strength of the ambient flow through the curtain (that is, over the diffuser):

$$F_a = \frac{U_a^3}{b} \tag{5}$$

where U_a = average current velocity over the depth ($m\ s^{-1}$)

b = buoyancy flux per unit length of diffuser

$= g \cdot \frac{\Delta\rho}{\rho_{sea}} \cdot \frac{Q}{L} \quad (m^{-3} s^{-3})$

Q = total flow into diffuser ($m^3\ s^{-1}$)

L = length of the diffuser (m)

A useful finding was that increased dilution is negligible for a Froude Number (F_a) less than about 0,1.

The resulting expression for initial dilution (current perpendicular to diffuser) after rigorous laboratory testing is given as:

$$S_{av} = 0{,}58 \cdot \frac{U_a \cdot h}{Q \cdot L} \tag{6}$$

ii. Wright (1984)

This theory is more applicable as it refers to individual rising plumes and makes provision for a linear, stratified environment.

The vertical density profile present in the ambient sea water, causes the plume to entrain denser water close to the bottom so that the density of the diluted plume could equal that of the surrounding sea water at some intermediate height before reaching the sea surface. Wright (1984) describes the intermediate height above the port at which the plume stops as z_m where:

$$Z_m = 2,3 (g^1 . \quad q_p / U_a)^{\frac{1}{3}} . G^{-\frac{1}{3}} \qquad (7)$$

and q_p = port flow $(m^3 s^{-1})$

G = density gradient parameter

$$= \frac{g}{\rho_{sb}} . \frac{(\rho_{ss} - \rho_{sb})}{h}$$

ρ_{sb} = density of sea water at sea bed $(g\ ml^{-1})$

ρ_{ss} = density of sea water at surface $(g\ ml^{-1})$

g^1 = relative density parameter

$$= g \left(\frac{\rho_a - \rho_{eff}}{\rho_a} \right) (ms^{-2})$$

ρ_a = average density of water column $(g\ ml^{-1})$

$$= \left(\frac{\rho_{sb} + \rho_{ss}}{2} \right)$$

Having computed the value of z_m Wright (1984) then derives the average dilution S_{av} as:

$$S_{av} = 0,25 \, . \, U_a \, . \, \frac{z_m^2}{q_p} \qquad (8)$$

However, after work by Chu (1979) and Roberts (1984) the coefficient of 0,25 was increased to 0,71:

$$S_{av} = 0,71 \, . \, U_a \, . \, \frac{z_m^2}{q_p} \qquad (9)$$

If z_m is found to exceed the water depth (h) then h can be substituted for z_m in equation (9).

This approach relates to a buoyancy dominated 'far field' condition, where the term 'far field' is used to define the receiving regime, i.e. that the rising plume is influenced by currents and must not be confused with *secondary dilutions* (i.e. the dilution which takes place after the initial dilution process) .

(Further explanation of the development of this approach can be found in Wright (1977-1), Wright (1977-2) and Koh (1983).

iii. EPA (1985)

The US Environmental Protection Agency (EPA) have published standard computer programs that are recommended for use in the evaluation of initial dilution in a standard way in the design stage.

Original programs published by Baumgartner *et al.* (1971) were updated in EPA (1985). One program, OUTPLM, computes rise heights and initial dilutions for moving water, non-uniform sea states, although the same program can also be used for stagnant, uniform sea states.

iv. WRc (1990)

As described previously in this Chapter the WRc (1990) suggests an approach where buoyancy dominated and current dominated conditions (BDC and CDC) are considered for achievable initial dilutions.

A CDC exists if:

$$y > 5.B/U_a^3$$

The achievable surface dilutions are given by:

$$S = C\,(U_a.h^2)/q_p$$

As for a buoyant dominated condition, statistical analysis of field data by WRc (1990) has provided C-values for a current dominated condition which correspond to different probabilities of exceedance for minimum initial dilutions. The C-values for a current dominated condition according to WRc (1990) are:
where:

C = 0,11 for 95% exceedance
C = 0,27 for median values (50%)
C = 0,32 for mean values (40%)

The four methods discussed above, i.e. Roberts (1977), EPA (1985), Wright (1984) and WRc (1990), were all used for the prediction of initial dilutions in this report. The first three theories were applied in the original feasibility studies (design as well as in later assessments of the outfalls concerned). The WRc (1990) approach has now been included because it is based on a simpler approach, which is very useful when extensive field data are not available. This technique to predict initial dilutions, can be a valuable tool if proven to be applicable to South African conditions, where 'quick' assessments of achievable dilutions for existing pipelines are frequently required.

3.2 Field Experiments

3.2.1 General

Rhodamine-B dye was used as tracer material because of characteristics such as low temperature effect, lowest measurable concentration by a fluorometer, slow photochemical decay, non-toxicity to marine life and its availability in South Africa. According to Toms and Botes (1987) the most ideal substance to use as tracer material is Pontacyl Pink, however, this is not readily available and is expensive.

A Turner-design fluorometer, capable of accurately measuring concentrations in a range from 0,0001 $\mu g\ l^{-1}$ to 1 $\mu g\ l^{-1}$, was used for the analysis. Samples having concentrations higher than 1 $\mu g\ l^{-1}$ were diluted to comply with the measuring range of the fluorometer.

Concentrations in the 'boil' of a rising buoyant jet vary considerably due to various physical influences as well as the sampling strategy. As the main purpose of this study was to measure initial dilutions, as many samples as possible were taken in the area at the 'boil' for the three test sites. The concentrations were then inspected and a range of samples was selected to be representative of the initial dilutions. The criteria for selection were:

i. *Specific period.* As the dye release is in the form of a pulse (not a continuous release) initial dilutions are only relevant between the time that the effluent is discharged from the ports and the time that the effluent reaches the sea-surface (or gets trapped below the surface due to stratification).

ii. *Distance from the discharge location.* Care had to be taken to exclude samples already subjected to secondary dilutions (due to transport). Based on a theoretical estimation of the geometry of the plume for each discharge location, only samples inside the plume ('boil') were used for the estimation of the initial dilutions.

iii. *Too many samples of low concentrations can influence the representativeness of the distribution of the initial dilutions.* Sampling took place continuously and because positioning in the boil is a difficult manoeuvre when adverse current and wind conditions are encountered, the number of lower concentrations can influence the representativeness of the distribution. A typical distribution for initial dilutions according to WRc (1990) was used as a guideline (a suggested mean of 30% and 40% exceedances for stagnant and moving water conditions, respectively). The range of the lower concentrations was adjusted i.e. concentrations less than 10% of the maximum concentrations were neglected.

3.2.2 Specific procedures

i. Richards Bay marine outfall for buoyant effluent (A-line)

This exercise was performed on 11 September 1991. One hundred litres of Rhodamine B dye was pre-diluted to 1 in 5 with fresh water (total volume: 500 *l*) and injected uniformly over a period of 600 *s* upstream of the pumps of the A-line. The dye was thoroughly mixed with the effluent in the pumps and samples that were taken downstream of the pumps during the injection period were used for the initial concentrations. To determine whether absorption of dye took place in the 5 *km* long pipeline, divers collected samples at *~30* s intervals at port number 30 of the diffuser. Due to an under-estimation of the travel time of the dye in the pipe and limited diving time in 29 *m* water depth this part of the exercise had to be repeated the following day (12 September 1991). By knowing the degree of absorption the dilutions were interpreted as the ratio of the measured concentration on the surface and the adjusted (for absorption) concentrations downstream of the pumphouse.

Due to a lack of flow metering facilities, the flow rates were estimated by the recording of the exact travel time of the dye between the pumphouse and the diffuser.

A Portnet survey vessel, equipped with electronic position fixing facilities, was used for measuring surface and subsurface currents, density profiles, and for positional sampling and circumnavigation of the moving effluent field.

Two ski-boats (one previously engaged in the diving operations during earlier stages of the exercise) were used to collect samples in the 'boil'. The aim was to collect as many samples as possible in the 'boil' for the determination of the initial dilutions. A light aircraft was used for the photographic recording of the effluent (plume) behaviour. However, due to the high dilutions from the 75 mm ports and poor visibility on the day of the exercise this effort was not successful.

ii. Mossgas pipeline in Vlees Bay

One hundred litres of Rhodamine B dye was pre-diluted to 1 in 5 with fresh water (total volume: 500 *l*) and injected into the intake of the outfall. To determine whether any absorption of Rhodamine-B occurred over the 9 *km* pipeline length, samples were taken downstream of the pumps during the injection period and at port number 1 of the diffuser at ~30 *s*. The sampling at the port was done by divers and at the surface through a pipe previously installed in the port. The volume of effluent in the storage reservoir was sufficient to run the pumps for approximately three hours before the release to ensure that a continuous discharge rate would be maintained during the test. A small amount of tracer was released approximately one hour before the main release to determine the scheduling of activities at sea during the test. Because a complete set of samples at the diffuser could be captured, the measured dilutions were determined by the ratio of the measured concentrations at the diffuser and that on the sea-surface.

The discharge rate based on the specifications of the pump was 250 $m^3\ h^{-1}$ (0,069 $m^3\ s^{-1}$) for this field exercise. The flow rate was also estimated by recording the total travel time of the dye (refinery to diffuser) giving a flow rate of 0,080 $m^3\ s^{-1}$ (288 $m^3\ h^{-1}$).

A fishing vessel, equipped with an electronic position fixing system, was used for the measurement of surface and subsurface currents, density profiles, and for positional sampling and circumnavigation of the moving effluent field. An inflatable boat was used for the diving operations and to obtain the samples from the diffuser. A helicopter was used for the photographic recording of the effluent (plume) behaviour.

iii. Marine outfall at Hout Bay

On 6 October 1993, just prior to the exercise, five ports were opened at the seaward end of the diffuser. At the time of the exercise the domestic sewage system was not yet connected to the outfall. Ground water flow to the pump station was between 0,030 and 0,040 $m^3\ s^{-1}$. In order to maintain a constant flow of between 0,120 and 0,130 $m^3\ s^{-1}$ during the exercise an additional 0,090 $m^3\ s^{-1}$ was pumped from the Disa River into two manholes approximately 150 m from the pump station. This was done by using two mobile centrifugal pumps.

The first preliminary run was done on 6 October 1993. Because of uncertainties as to the hydraulic behaviour of the entire system and stratification in the water column, resulting in the complete trapping of the dye below the surface, a second preliminary run had to be conducted on 11 October 1993. Although the dye was again trapped below the surface at approximately 10 m, the hydraulic behaviour of the system, including the choking procedure from the river, was sorted out. The reading of the flow meter at the treatment works also correlated well with the flow which was estimated from recording the travel time between the Disa River pump station and the treatment works (dye tracers were injected a few times). It was possible to maintain a constant flow of 0,122 $m^3\ s^{-1}$ for several hours.

Thirtythree litres of Rhodamine B dye was pre-diluted with fresh water to 1 in 5 (total volume: 165 *l*). A dye tracer was released one hour prior to the main release in order to facilitate operations at sea.

A fishing vessel, equipped with an electronic position fixing system, was used for positional sampling in the 'boil' and circumnavigation of the surface effluent field. A ski-boat, also equipped with an electronic position fixing system was used for the measurement of surface and sub-surface current, density profiles and positional sampling in the boil. Throughout the operation, samples from the diffuser were collected through the previously installed 12 *mm* diameter pipe, using an inflatable boat. When it was observed that most of the effluent was trapped below the surface, divers sampled in the sub-surface plume ('boil') which was situated between 5 *m* and 10 *m* below the surface. Photographs were taken from the shore (elevation 330 *m*). Due to the partial trapping of the dye during the exercise and the high dilutions at the surface, the effluent plume was not clearly distinguishable from this point.

4. RESULTS AND DISCUSSION

4.1 Richards Bay Marine Outfall for Buoyant Effluent (A-line)

4.1.1 Predictions

The following data and assumptions were used as input conditions for the Richards Bay predictions:

Flow:
(a) 1,35 $m^3\ s^{-1}$ (Calculated from recorded travel time of dye in the outfall pipe)
(b) Constant flow

Density of effluent:
1 010,1 $g\ l^{-1}$ (Determined by conservation of mass from measured salinity of the added seawater, raw effluent and the final effluent).

Diffuser:
(a) All 96 ports were discharging without any obstruction (blockage).
(b) Dilutions were determined for the worst performing 115 *mm* diameter port (i.e. the port with the highest flow rate)

Currents and stratification:
(a) Velocities measured between -20 *m* depth and the sea bottom were estimated (observation by divers - travel time of neutral buoyant object).
(b) Conditions were recorded before and after the exercise (Table 4). Conditions (currents/stratification) at the time when the dye reached the diffuser were estimated by interpolation of the before and after measurements of the physical conditions as shown in Table 1.
(c) For the applications according to WRc (1990) and Wright (1984) an average ambient velocity of 0,32 $m\ s^{-1}$ was used.

Table 1. Richards Bay: Current and density profiles used in the dilution predictions

DEPTH (m)	DENSITY ($g\ l^{-1}$)	CURRENT VELOCITY ($m\ s^{-1}$)
0	1 024,82	0,56
-5	1 024,96	0,41
-10	1 025,03	0,35
-15	1 025,08	0,32
-20	1 025,12	0,20
-28	1 025,16	0,15

4.1.1.1 Stagnant uniform theory

The various theories on initial dilutions that can be achieved by the entrainment of ambient seawater into a rising buoyant effluent plume are described in detail in Chapter 2. The minimum dilutions that could be achieved for a total discharge rate of 1,35 $m^3\ s^{-1}$, an effluent density of 1 010 $g\ l^{-1}$ and a 115 mm diameter port in a uniform stagnant ambient environment according to Roberts (1977) and an EPA (1979) program are 109 (average 189) and 137 (average 238), respectively. According to WRc (1990) the achievable dilutions for 'stagnant' conditions, i.e. a buoyancy dominated condition (BDC), are 180, 300 and 380 representing 95 percentiles, median and mean values, respectively.

Table 2. Richards Bay: Predicted dilutions for stagnant uniform conditions (also refer to Table 8)

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Roberts (1977)	109	147	*	189
EPA (1985)	137	184	*	238
WRc (1990)		180	300	380

* **Assumption: Gaussian distribution**

4.1.1.2 Moving water theory

The various approaches to determining the dilutions that can be achieved in moving water (currents) and in a non-uniform medium (vertical density gradients) when a buoyant effluent is discharged, are also given in Chapter 2.

The EPA (1985) computer model makes provision for the input of various density and velocity profiles and is normally applied if such data is available. This method (EPA, 1985) and that of Wright (1984) and the WRc (1990) approaches were applied to determine the predicted dilutions that could be achieved during the Richards Bay field exercise. As shown in Section 4.1.2.1 and Figure 3 the physical conditions changed during the day due to increasing wind velocities from the north east, resulting not only in increased current velocities but also in increased water temperatures and consequent lower densities that affected the vertical rise of the buoyant plume of which the density was assumed to be unchanged.

The predicted dilutions for the simulated conditions (Table 1) at the time of discharge are given in Table 3.

Table 3. **Richards Bay: Predicted dilutions using the actual physical conditions on 11 September 1991** (Also refer to Table 8)

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Wright (1984)	827	1 110	*	1 440
EPA (1985)	770	1 040	*	1 340
WRc (1990)	-	750	1 830	2 170

* **Assumption: Gaussian distribution**

The dye surfaced 65 *m* south west of the 115 *mm* diameter port section of the diffuser compared to a predicted 62 *m* by the EPA program which proved the validity of the EPA program with regard to the prediction of the geometry of the rising plume. The geometrical prediction of the plume using the EPA program is also recommended by WRc (1990).

4.1.2 Field experiment

4.1.2.1 Weather and sea conditions

The Richards Bay field experiments were conducted during calm to moderate north to north-easterly conditions, with strong north-easterly conditions during the two days before the exercise, which was the cause for relatively strong south-westerly currents on the day of the exercise.

The weather and sea conditions on the day of the exercise (11 September 1991) are summarized in Table 4.

Table 4. Richards Bay: Weather and sea conditions measured on 11 September 1991

TIME	08:50	09:35	11:30	12:07
WIND: Speed ($m\ s^{-1}$)	1,7		9,4	
Direction	0°		45°	
CURRENTS:				
Surface: Speed ($m\ s^{-1}$)		0,47		0,63
Direction		202°		202-225°
-5 m: Speed ($m\ s^{-1}$)		0,34		0,48
Direction		202°		202-225°
-10 m: Speed ($m\ s^{-1}$)		0,32		0,38
Direction		202°		202-225°
TEMPERATURE (°C): Surface	20,91		21,21	
- 5 *m*	20,87		21,14	—
- 10 *m*	20,60		20,97	
- 15 *m*	20,53		20,64	
- 20 *m*	20,52		20,56	
- 25 *m*	20,49			
SALINITY: Surface	35,37		35,20	
- 5 *m*	35,39		35,19	
- 10 *m*	35,40		35,20	
- 15 *m*	35,41		35,18	
- 20 *m*	35,45		35,22	
- 25 *m*	35,47			

Although current speeds (especially surface currents) increased during the exercise due to an increase in wind speed from 1,7 to 9,4 $m\ s^{-1}$ (3 to 17 *knots*), there was only a slight shift in current direction from south south-west to a more south-westerly direction. The north-easterly wind also caused a slight increase in sea temperatures, i.e. 0,3 °*C* at the surface and 0,1 °*C* at -15 *m* depth. The trajectories and velocities of surface and sub-surface currents are illustrated in Figure 3.

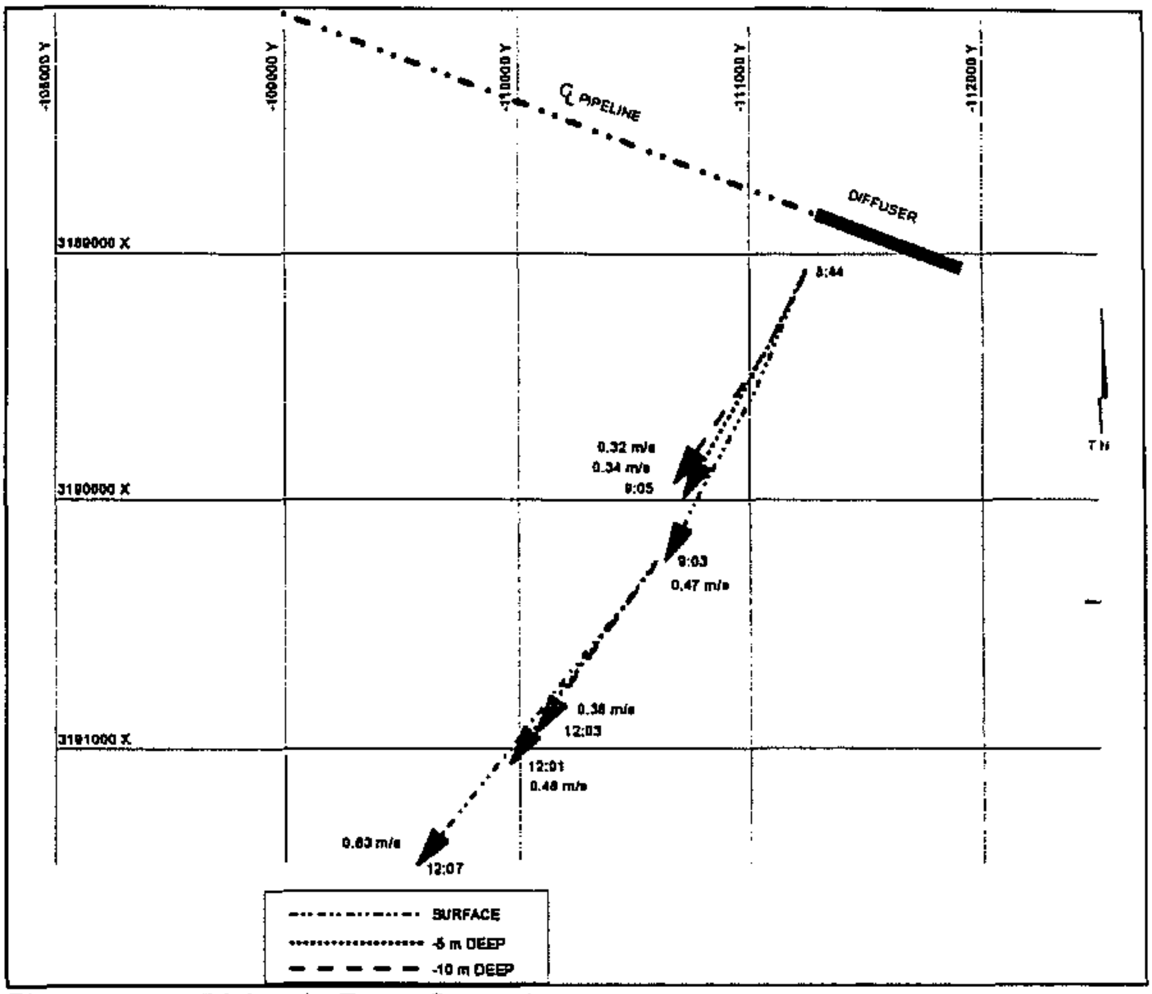

Figure 3. Richards Bay: Currents

4.1.2.2 Specific details on dye release

Details of the Rhodamine B dye injection and the measured and estimated concentrations at the diffuser (port number 30) for the test on 11 September 1991 and on 12 September 1991, when the exercise was repeated, are as follows:

Table 5. Richards Bay: Details of the dye release on 11 and 12 September 1991

	1991/09/11	1991/09/12
INJECTION:		
Volume of Rhodamine (*l*)	100	25
Pre-dilution	1 in 5	1 in 5
Total volume of dye (*l*)	500	125
Time of release	9:25	8:32
Duration of release (*s*)	600	150
Pump discharge rate ($l\ s^{-1}$)	1 350 *	1 070 *
Conc. at pump ($mg\ l^{-1}$)	102	22
Time of surfacing	10:11	9:28
Travel time (*min*)	46	58
AT THE DIFFUSER:		
Highest concentration ($mg\ l^{-1}$)	102 **	23
2nd highest concentration ($mg\ l^{-1}$)		16

* Estimate: Based on total travel time

** Estimate: From the exercise conducted on 12 September 1991 evidently absorption and longitudinal dispersion in the pipeline caused no reduction in the highest concentrations.

Measured concentrations at the pumphouse and the diffuser are shown in Figure 4. Based on theoretical average flow rates when all the pumps on the buoyant line (A-line) were running at full capacity (DWAF, 1991), the discharge rate of the final effluent was estimated as 1,757$m^3\,s^{-1}$. A more accurate estimate was made by recording the actual travel time between the pumphouse and diffuser that resulted in a total flow of 1,350 $m^3\ s^{-1}$.

Table 6. Richards Bay: Calculated flow rates

	SALINITY		FLOW ($m^3\ s^{-1}$)
	Range	Average	
Inflow	4,3 - 4,4	4,17	0,817
Seawater	33,1 - 33,4	33,27	0,533
Outflow	14,2 - 17,1	15,78	1,350

To determine the theoretical dilutions that can be achieved, the effluent density must be known. Assuming the density of raw effluent to be 990 $g\ l^{-1}$ and that of the additional 533 $l\ s^{-1}$ seawater to be 1 026 $g\ l^{-1}$, the estimated density of the final effluent was 1 010,1 $g\ l^{-1}$ (conservation of mass) which compared well with a measured value of 1 010,2 $g\ l^{-1}$.

4.1.2.3 Measured initial dilutions

To determine the minimum surface dilutions as many samples as possible were taken in the visible 'boil' above the diffuser. The 'boil' could be detected visually only above the six 115 *mm* diameter ports on 11 September 1991. On the following day when a reduced volume of dye was released for the determination of the absorption in the pipeline, the effluent (dye) was also visible above the other ports (75 *mm* diameter) although visibility was significantly less than at the 115 *mm* diameter ports. This could be due to weaker currents on 12 September 1991 that would affect the dilutions that could be achieved (Table 5).

On 11 September 1991 the dye surfaced 65 *m* south west (that is in the direction of the current) from the 115 *mm* diameter diffuser ports.

The ratio of the concentration inside the diffuser and the highest concentration in the 'boil' was taken as the minimum dilution. The highest concentration encountered in a total of 469 samples was 0,125 $mg\ l^{-1}$ and occurred at 10:22, 11 minutes after the dye was visible for the first time. This yielded a minimum dilution of 820; that is the minimum dilution achievable for the 115 *mm* diameter ports. The measured concentrations versus time are illustrated in Figure 4.

Due to the different surfacing patterns of the two types of diffusers, the sampling procedure in the 'boil' was upset, but it can be confidently assumed that the highest concentration (minimum dilution) was detected. According to WRc (1990) the skewness of a frequency distribution of the minimum dilutions is typically positive with a mean representing a 40% exceedance value. To determine the

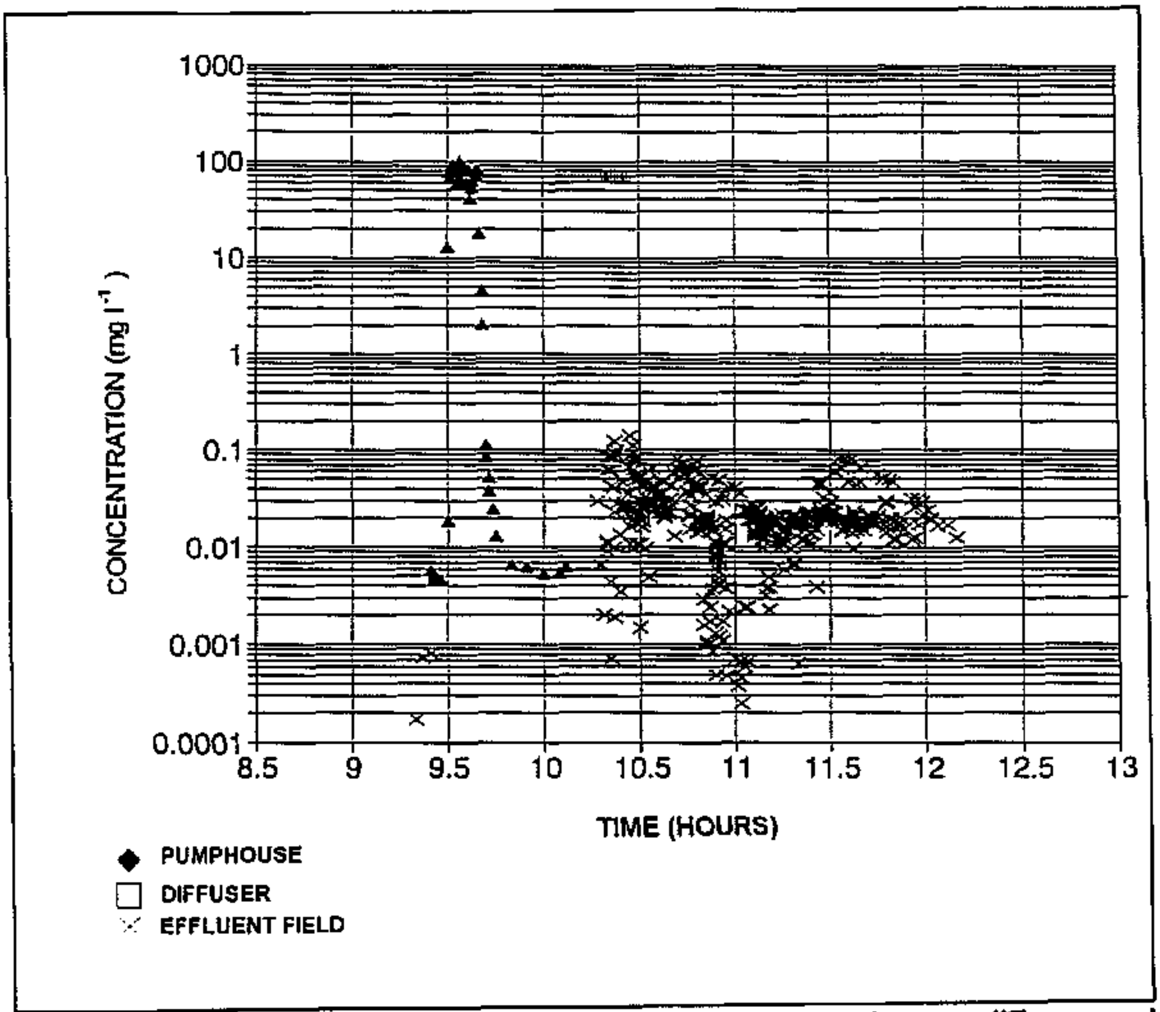

Figure 4. Richards Bay: Concentrations in the pump house, diffuser and effluent field

initial dilution 54 samples (which complied to the criteria set in Section 3.2.1 between 10:20 and 10:40) were statistically analysed and yielded a mean, median and 95 percentile of 2 140, 1 890 and 930, respectively (standard deviation of 1 072). Frequency distributions for the concentrations used to determine the initial dilutions are illustrated in Figure 5.

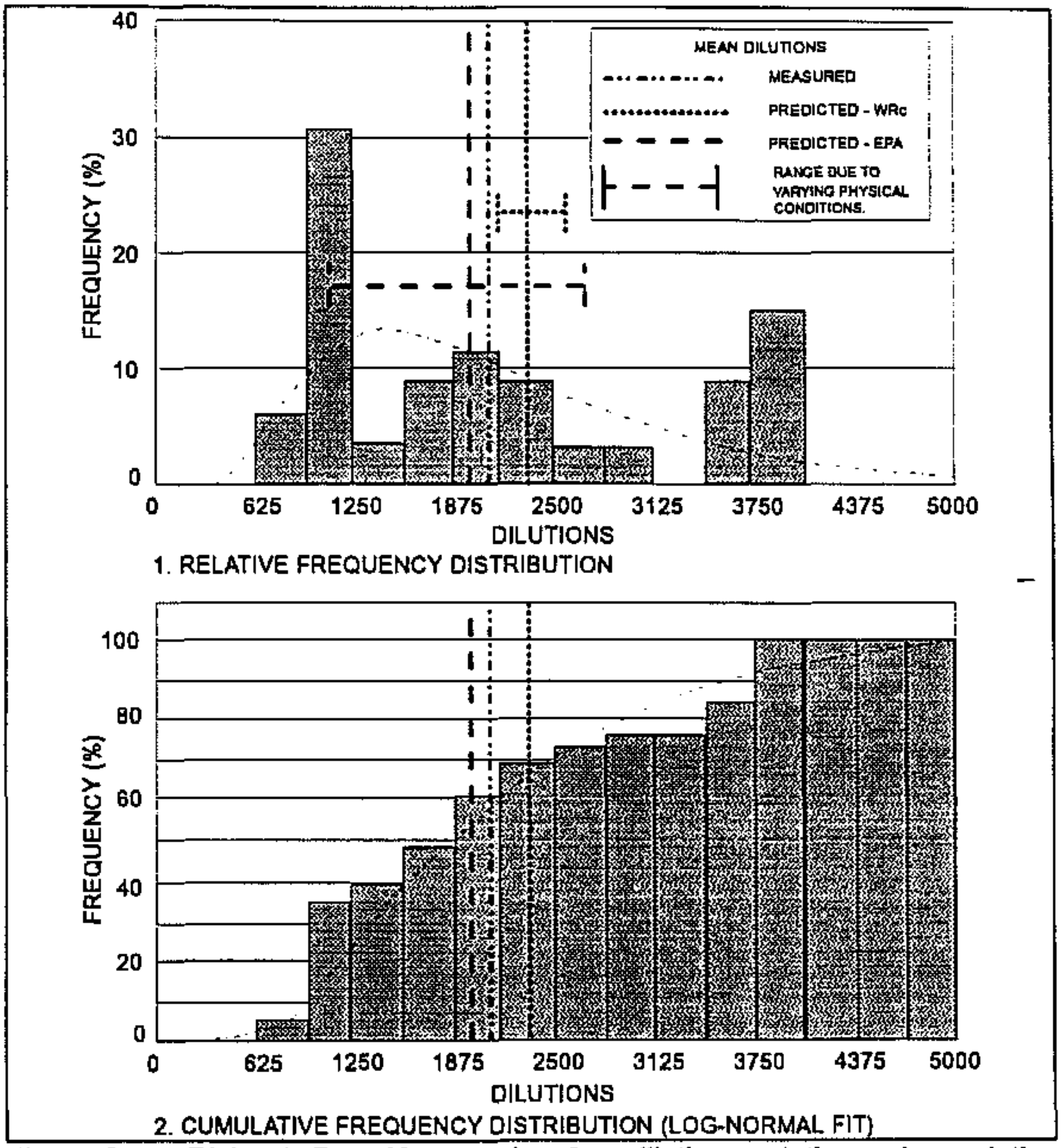

Figure 5. **Richards Bay: Measured surface dilutions, relative and cumulative frequencies**

On 12 September 1991 the standby boat for the divers took a limited number of samples (45) in the 'boil' and a maximum concentration of 1 045 $mg\ l^{-1}$ was recorded which yielded a minimum dilution of 511, three minutes after the dye was visible for the first time. These lower initial dilutions, in comparison to the previous day, were due to weaker currents which were observed (not recorded). As mentioned before, the plumes from the 75 *mm* diameter ports were also visible on 12 September 1991.

4.1.2.4 Transport and secondary dilutions

The surface effluent field was monitored by circumnavigation (electronic position fixing) at certain intervals as it moved to the south west with the current. Samples were continuously taken in the moving effluent field to determine the degree of secondary dilutions (Refer to Chapter 1) that could be achieved. As for the initial dilutions, the behaviour of the effluent surface waste field was not representative for the total A-line diffuser, but only for the six 115 *mm* diameter ports.

On four occasions (Table 7) the perimeter of the surface effluent field was determined and its displacement is illustrated in Figure 6a. The achievable dilutions versus distance from the discharge location are illustrated in Figure 6b.

Table 7. Richards Bay: Times when the effluent field was monitored

TIME	TIME AFTER SURFACING (*min*)
10:36	25
10:58	47
11:19	68
11:49	98

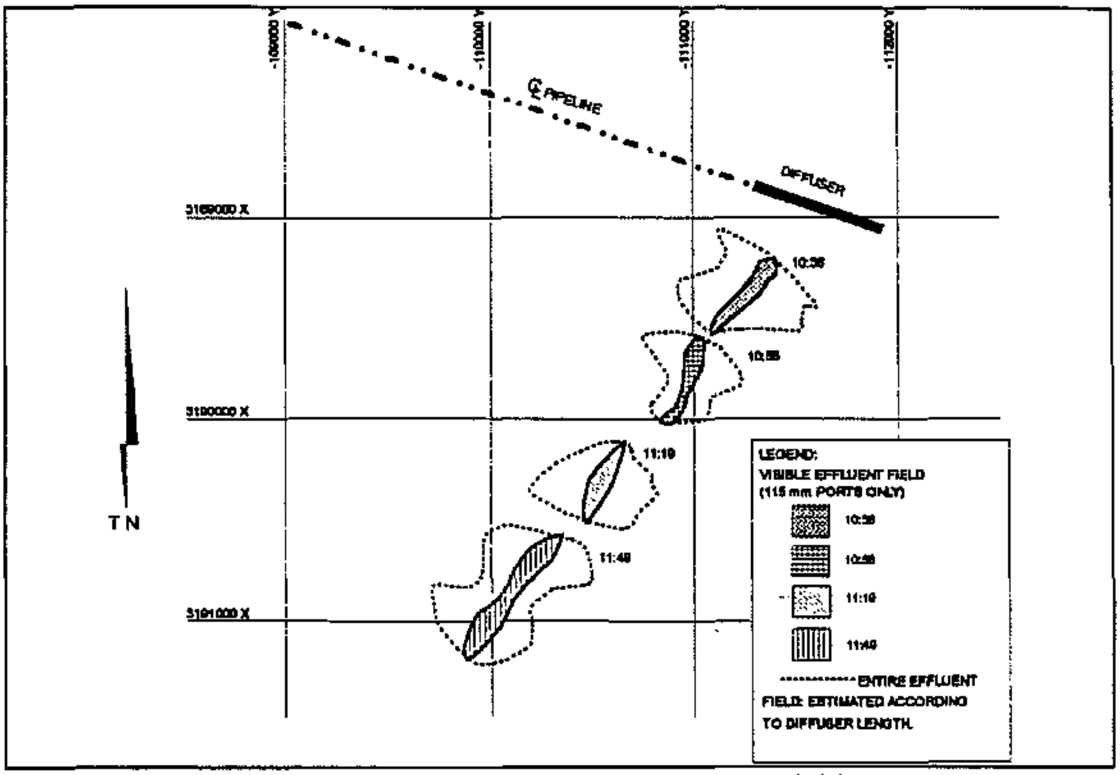

Figure 6a. Richards Bay: Transport of the effluent field

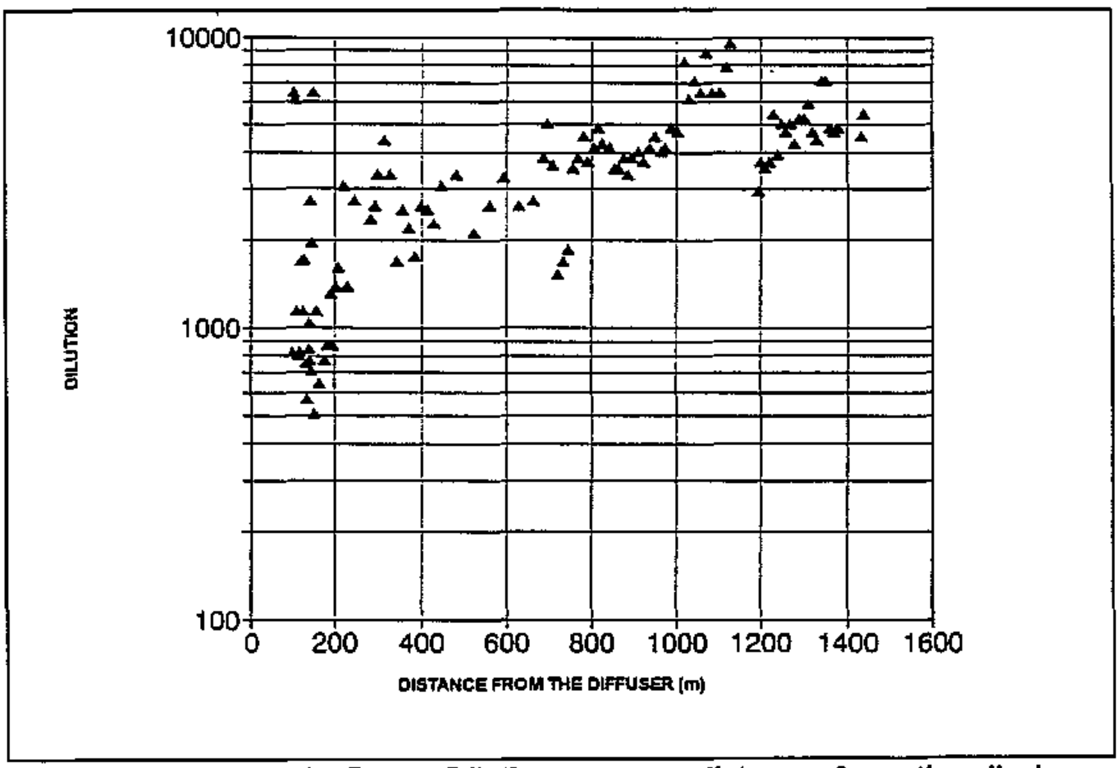

Figure 6b. Richards Bay: Dilutions versus distance from the discharge location

4.1.3 Comparison of results

The theoretical predictions for stagnant uniform conditions by Roberts (1977), EPA (1985) and WRc (1990) and predictions according to moving water theories (EPA, 1985; WRc, 1990) as well as the measured prototype dilutions on 11 September 1991 are as follows:

Table 8. Richards Bay: Predicted dilutions versus measured dilutions

		MINIMUM	95 PERCENTILE	MEDIAN	MEAN
MEASURED		820	930	1 890	2 140
Stagnant Uniform	Roberts (1977)	109	147	*	189
	EPA (1985)	137	184	*	238
	WRc (1990)	-	180	300	380
Current/ stratified	Wright (1984)	827	1 110	*	1 440
	EPA (1985)	770	1 040	*	1 340
	WRc (1990)	-	750	1 830	2 170

* **Assumption: Gaussian distribution**

The comparison of the dilutions measured during actual conditions and those of the design criteria and the predicted dilutions for actual conditions are presented in Table 9.

Table 9. Richards Bay: Comparison of the dilutions measured during actual conditions and predicted dilutions for stagnant uniform and actual conditions

	MEASURED/PREDICTED (Stagnant Uniform)	MEASURED/PREDICTED (Moving water theory)
Roberts(1977):		
Minimum	7,5	NA
Mean	11,3	
EPA (1985):		
Minimum	6,0	1,1
Mean	9,0	1,6
WRc (1990):		
95 Percentile	5,2	1,3
Median	6,3	1,0
Mean	5,6	1,0
Wright (1984):		
Minimum		1,0
Mean	-	1,5

Although the stagnant uniform assumption is not realistic because of the dynamic conditions present on the day of the exercise, it must be kept in mind that the Richards Bay outfall design was based on stagnant uniform conditions and recommended water quality guidelines of 5 $mg\ l^{-1}$ for fluoride, taking a background of 1,5 $mg\ l^{-1}$ into account. Thus the application of stagnant uniform conditions to the Richards Bay outfall can result in under-estimations (conservative) of greater than six times for dilutions on days when current velocities exceed 0,3 $m\ s^{-1}$.

For the WRc approach the predicted dilutions for actual conditions compared extremely well with the measured conditions.

Toms and Botes (1987) concluded after a series of field tests in nearly stagnant conditions (Camps Bay) that by applying the stagnant uniform theory a safety factor of two to three times is included in the estimate of initial dilutions that can be achieved, which could be due to even very weak currents (0,05 $m\ s^{-1}$) which caused additional entrainment. This exercise at Richards Bay indicated that the safety factor (under-estimation) can increase to more than six times if the stagnant uniform theory according to Roberts (1984) and EPA (1985) is applied to more dynamic conditions, where the current velocities exceed 0,3 $m\ s^{-1}$.

4.2 Mossgas Pipeline in Vlees Bay

4.2.1 Predictions

The following data were used as input conditions:

Flow:	(a)	0,08 $m^3\ s^{-1}$ (Travel time and distance)
	(b)	Constant flow
Density of effluent:		1 000 $g\ l^{-1}$
Diffuser:	(a)	All 5 ports were discharging without any obstruction (blockage).
	(b)	Dilutions were determined for the worst performing port, i.e. the port with the highest flow rate. This was determined by an hydraulic analysis of the outfall system (inshore port number 5).

4.2.1.1 Stagnant uniform theory

The predicted average dilutions for a total discharge rate of 0,08 $m^3\ s^{-1}$ and an effluent density of 1 000 $g\ l^{-1}$ in a stagnant (no currents) uniform (no stratification) environment according to Fan and Brooks (1969) updated by Roberts (1984), the EPA (1985) program and WRc (1990) are given in Table 10. According to WRc (1990) a buoyancy dominated condition (BDC) existed on the day of the exercise, representing actual 'stagnant' conditions (Refer to Chapter 2).

Table 10. Vlees Bay: Predicted dilutions for stagnant uniform conditions

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Roberts (1977)	164	220	*	286
EPA (1985)	194	260	*	338
WRc (1990)	-	265	450	565

* Assumption: Gaussian distribution

Current conditions and the layering (stratification) of the water column on the day of the exercise (10 November 1992) can be classified as very 'stagnant and uniform'.

4.2.1.2 Moving water theory

The various approaches to determine the dilutions that can be achieved in moving water (currents) and in a non-uniform medium (vertical density gradients) when a buoyant effluent is discharged are given in Chapter 2.

The EPA (1985) computer model makes provision for the input of various density and velocity profiles and is normally applied if such data is available. This method (EPA, 1985) and that of Wright (1984) were applied to determine the theoretical dilutions that could be achieved during the Vlees Bay field exercise. As shown in Section 4.2.2.1 and Figure 7 the physical conditions changed slightly during the day due to the change in wind direction from south west to south east. Applying the WRc (1990) theory to the actual conditions measured on the day of the exercise, buoyancy dominated conditions (BDC), i.e. stagnant water, existed.

The achievable dilutions for the pre- and post-discharge conditions as determined by the EPA (1985) model, Wright (1984) and WRc (1990) are given in Table 11.

Table 11. Vlees Bay: Predicted dilutions based on actual physical conditions measured on 10 November 1992

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Wright (1984)	290-314	390-420	*	506-546
EPA (1985)	290-470	390-630	*	520-820**
WRc (1990)	-	265	450	565

* Assumption: Gaussian distribution

** The range is due to the slight change in current direction during the sampling exercise. Because conditions varied during the exercise an estimate of one representative condition was not possible.

The dye surfaced slightly north west of the diffuser.

4.2.2 Field experiment

4.2.2.1 Weather and sea conditions

The Vlees Bay field experiment was conducted during moderate to calm south west to south south-easterly conditions. The weather and sea conditions on the day of the exercise (10 November 1992) are summarized in Table 12.

Table 12. Vlees Bay: Weather and sea conditions on 10 November 1992

TIME	10:02	11:00	12:48	14:55	15:20
WIND: Speed ($m\ s^{-1}$)	5,6			2,8	
Direction	202°			187°	
CURRENTS:					
Surface: Speed ($m\ s^{-1}$)			0,18-0,15		0,11
Direction			0°		315°
-5 m: Speed ($m\ s^{-1}$)			0,18-0,07		0,09
Direction			315-337°		315°
-10 m: Speed ($m\ s^{-1}$)			0,10-0,06		0,06
Direction			337°		315°
TEMPERATURE (°C): Surface		18,20			18,46
- 5 *m*		18,16			18,46
- 10 *m*		17,98			18,21
- 15 *m*		17,94			18,20
- 20 *m*		17,89			18,20
- 25 *m*		17,81			18,10
SALINITY : Surface		34,73			34,64
- 5 *m*		34,72			34,65
- 10 *m*		34,72			34,65
- 15 *m*		34,73			34,65
- 20 *m*		34,74			34,65
- 25 *m*		34,75			34,65

Current speeds decreased slightly during the day, that is from 11:00 (before the test) to 15:00 (after the test) with a slight change in direction to north west due to a change in wind direction from south south west to south south east. The measured surface and subsurface currents before and after the test are illustrated in Figure 7. A seawater temperature increase of less than 0,5 °C and a drop in salinity of approximately 0,1 units between 11:00 and 15:00 were observed.

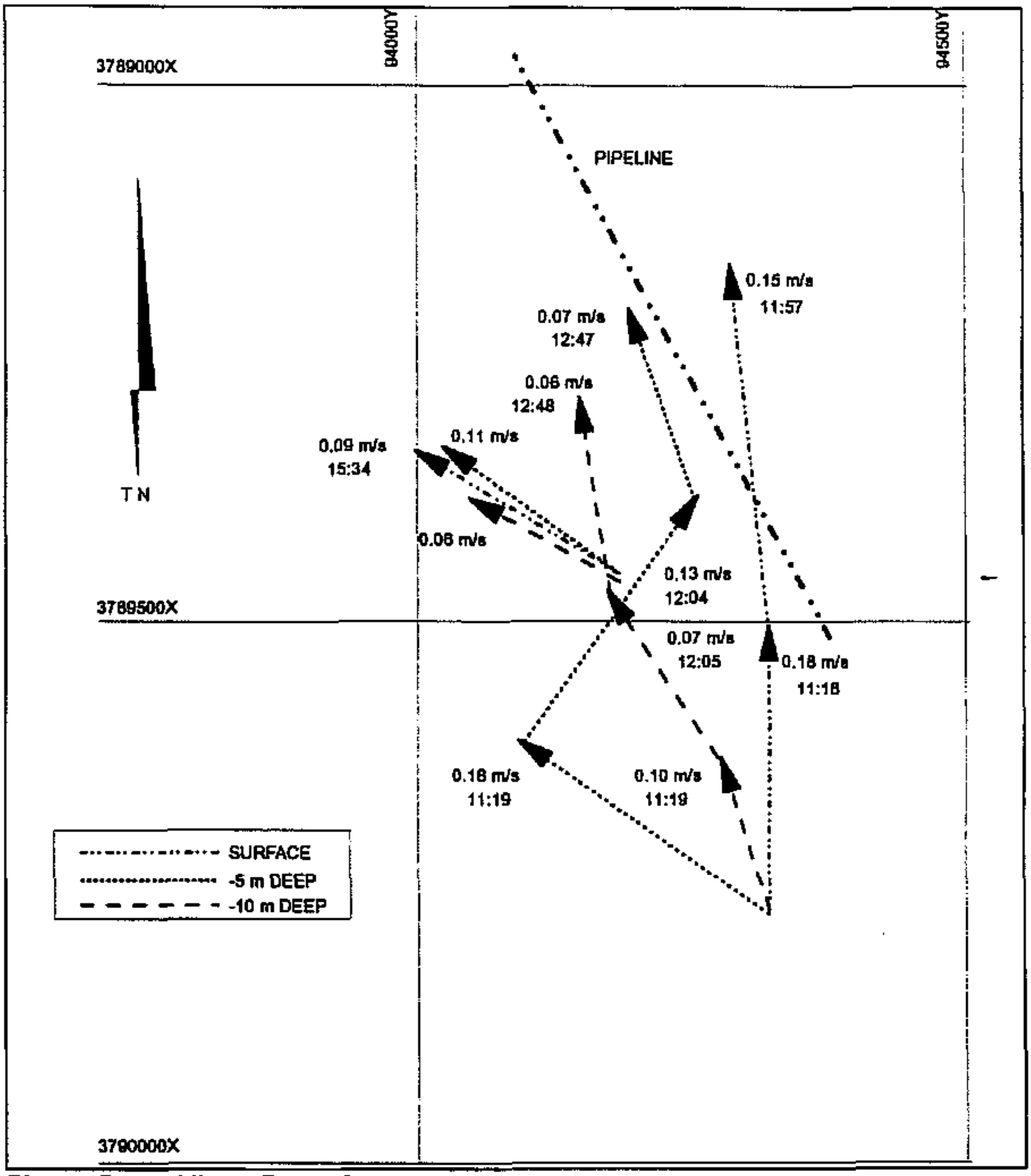

Figure 7. Vlees Bay: Currents

4.2.2.2 Specific details on dye release

Details of the Rhodamine B dye injection and the measured and estimated concentrations at the diffuser (port number 1) for the test on 10 November 1992 are given in Table 13.

Table 13. Vlees Bay: Details of the dye release on 10 November 1992

INJECTION:	
Volume of Rhodamine (*l*)	100
Pre-dilution	1 in 5
Total volume of dye (*l*)	500
Time of release	11:01
Duration of release (*s*)	1 440
Pump discharge rate ($l\ s^{-1}$)	69* (80)
Concentration at pump ($mg\ l^{-1}$)	500
Time of surfacing	13:12
Travel time (*min*)	131
AT THE DIFFUSER:	
Highest concentration ($mg\ l^{-1}$)	500
2nd highest concentration ($mg\ l^{-1}$)	484
Average from 13:19 to 13:32 ($mg\ l^{-1}$)	469

* **Estimate: Based on pump delivery rate (80 $l\ s^{-1}$ estimated from total travel time)**

Absorption of Rhodamine B dye between the pumphouse and the diffuser was insignificant. The measured concentrations at the pumphouse and the diffuser are shown in Figure 8. The density of the effluent was taken as 1 000 $g\ l^{-1}$. The average seawater density was approximately 1 025 $g\ l^{-1}$.

4.2.2.3 Measured initial dilutions

A total of 160 samples was taken from the diffuser (port number 1) between 13:10 and 15:30. The measured concentrations are illustrated in Figure 9. Between 13:19 and 13:32 the concentrations varied from 452 to 500 $mg\ l^{-1}$ with an average of 469 $mg\ l^{-1}$. This value (469 $mg\ l^{-1}$) was used as the input concentration for the determination of the achievable surface dilutions.

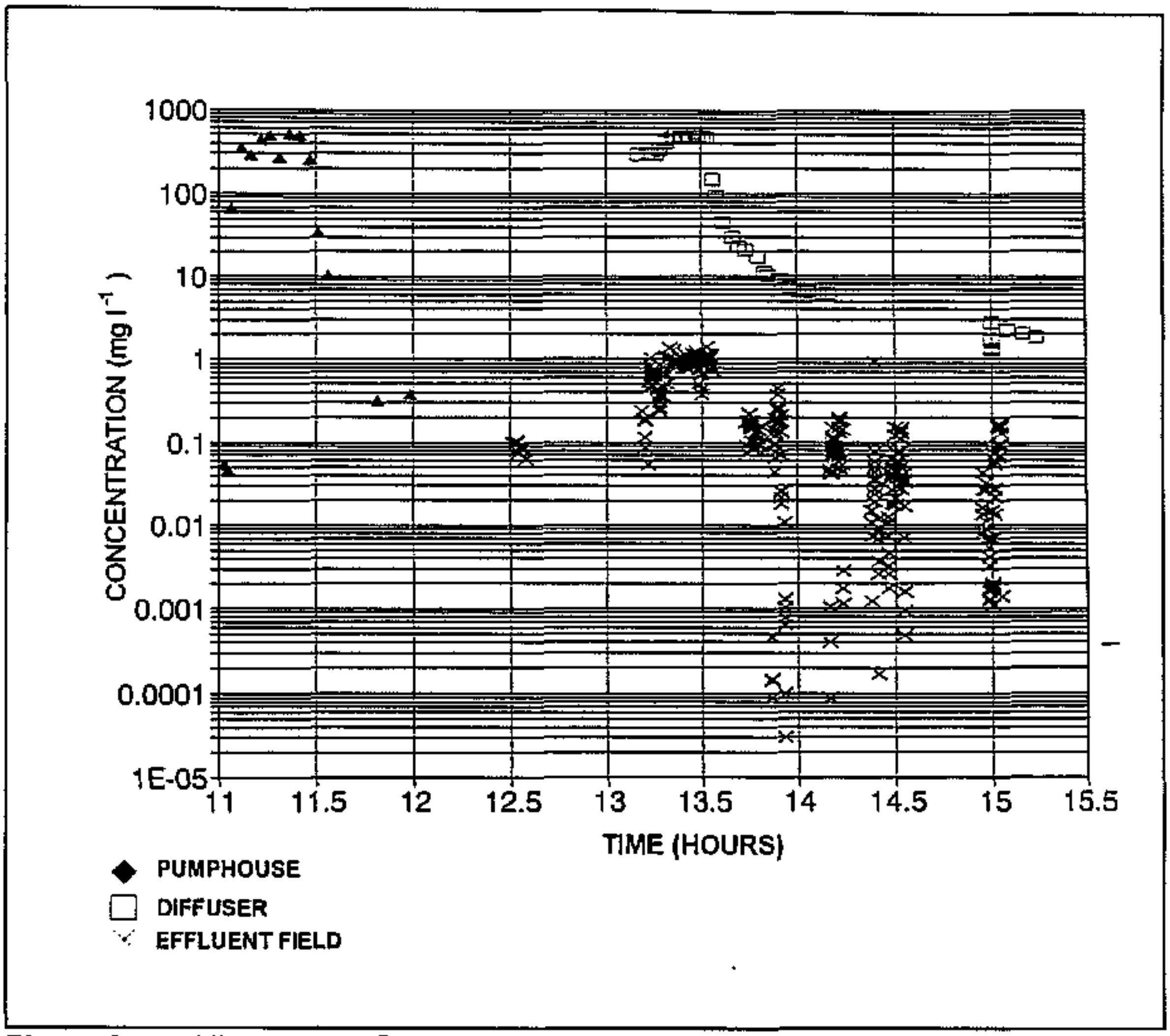

Figure 8. **Vlees Bay: Concentrations in the pump house, diffuser and effluent field**

To determine the minimum surface dilutions as many samples as possible were taken in the visible 'boil' above the diffuser. The dye surfaced almost at the diffuser due to the weak currents. The five 'boils' from the ports could easily be distinguished, which helped the sampling process and the recording of the highest concentrations (minimum dilutions) and a statistical representative distribution of dilutions could be obtained. The surfacing of the effluent plume ('boil') is illustrated in Figure 9.

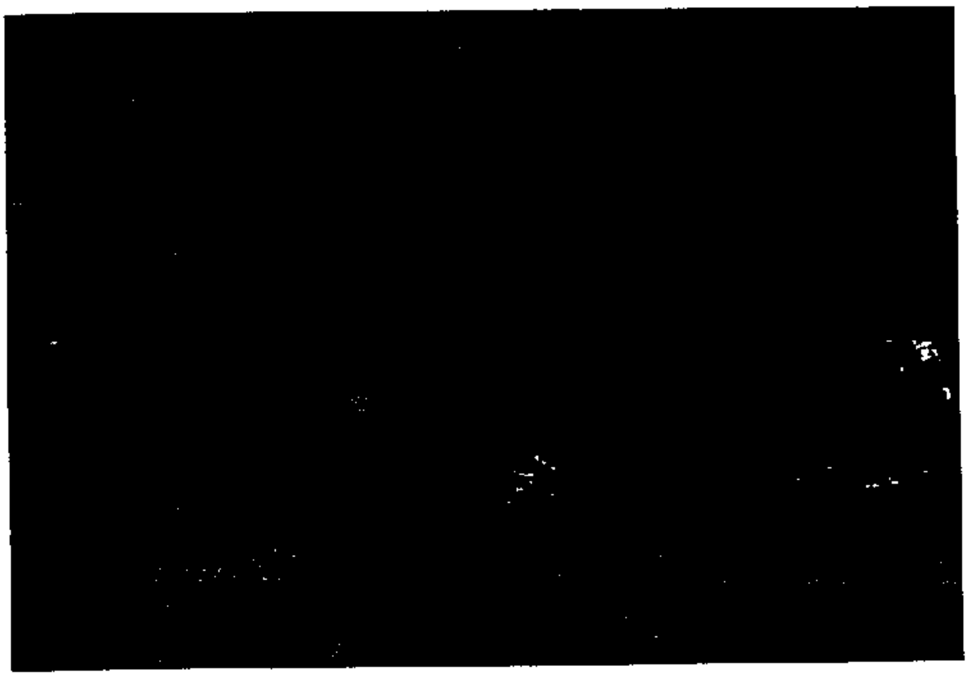

Figure 9. Vlees Bay: The surfacing effluent ('boil')

The ratio of the concentration at the diffuser (469 *mg ℓ'*) and the highest concentration in the 'boil' was taken as the minimum dilution. The highest concentration measured from a total of 469 samples was 1,4 *mg ℓ'* at 13:32, 20 minutes after the dye was visible for the first time, resulting in a minimum dilution of 335. From a total of 102 samples taken within 50 m from the diffuser and between 13:22 and 13:57 (see Chapter 3.2.1), 95% exceeded a dilution of 397 (concentration of 1,2 *mg ℓ'*) with median and mean values of 518 and 642, respectively (standard deviation of 303). These are similar to the values determined by WRc (1990) from field experiments. The relative frequency distributions and accumulative frequencies of the initial dilutions are illustrated in Figure 10.

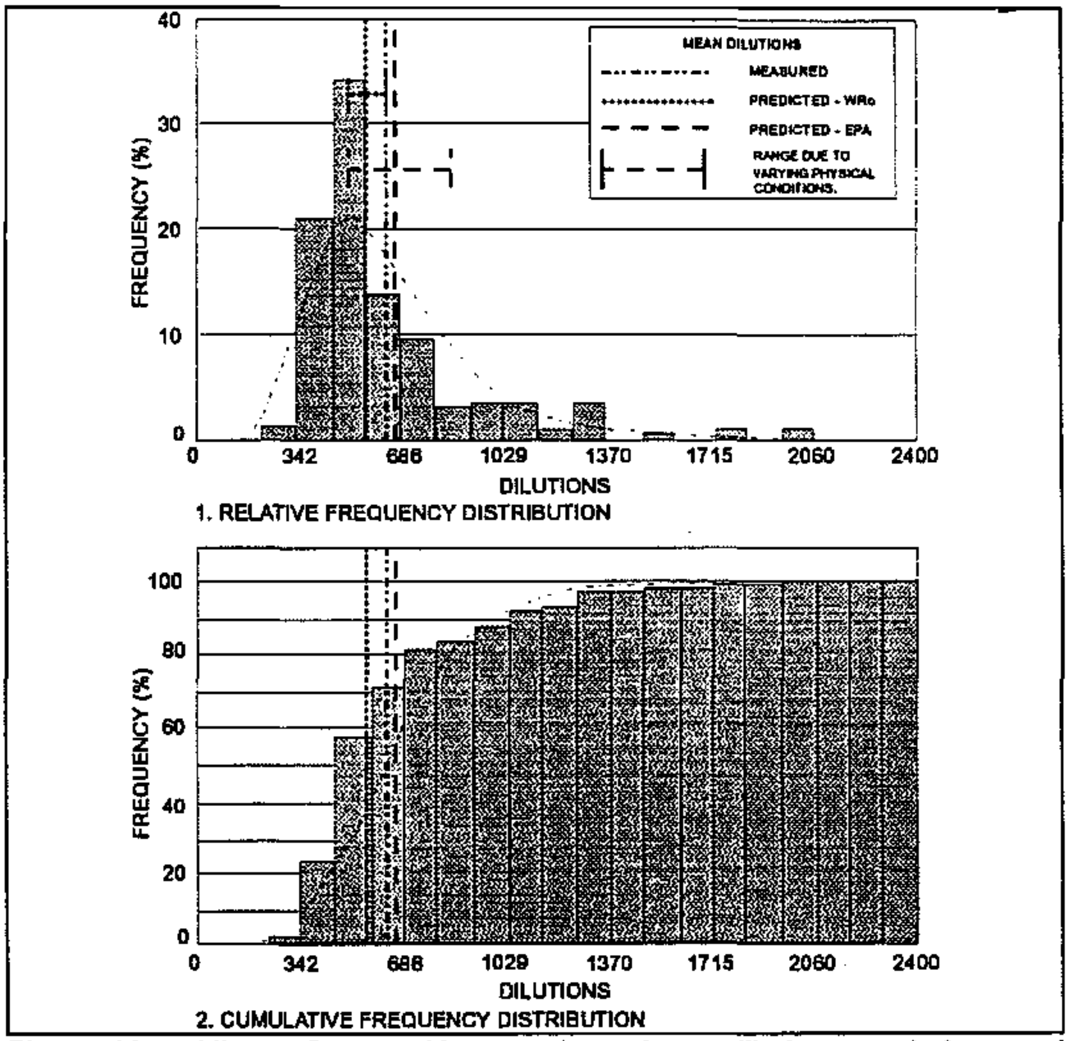

Figure 10. **Vlees Bay: Measured surface dilutions, relative and cumulative frequencies**

4.2.2.4 Transport and secondary dilutions

The effluent surface field was monitored by circumnavigation (electronic position fixing) on three occasions as it moved to the north west with the current. The spatial movement of the effluent field as described by the perimeters of the plume at 13:35, 14:00 and 14:40 is illustrated in Figure 11a. The dispersion of the effluent field is illustrated in Figures 11b (aerial photograph).

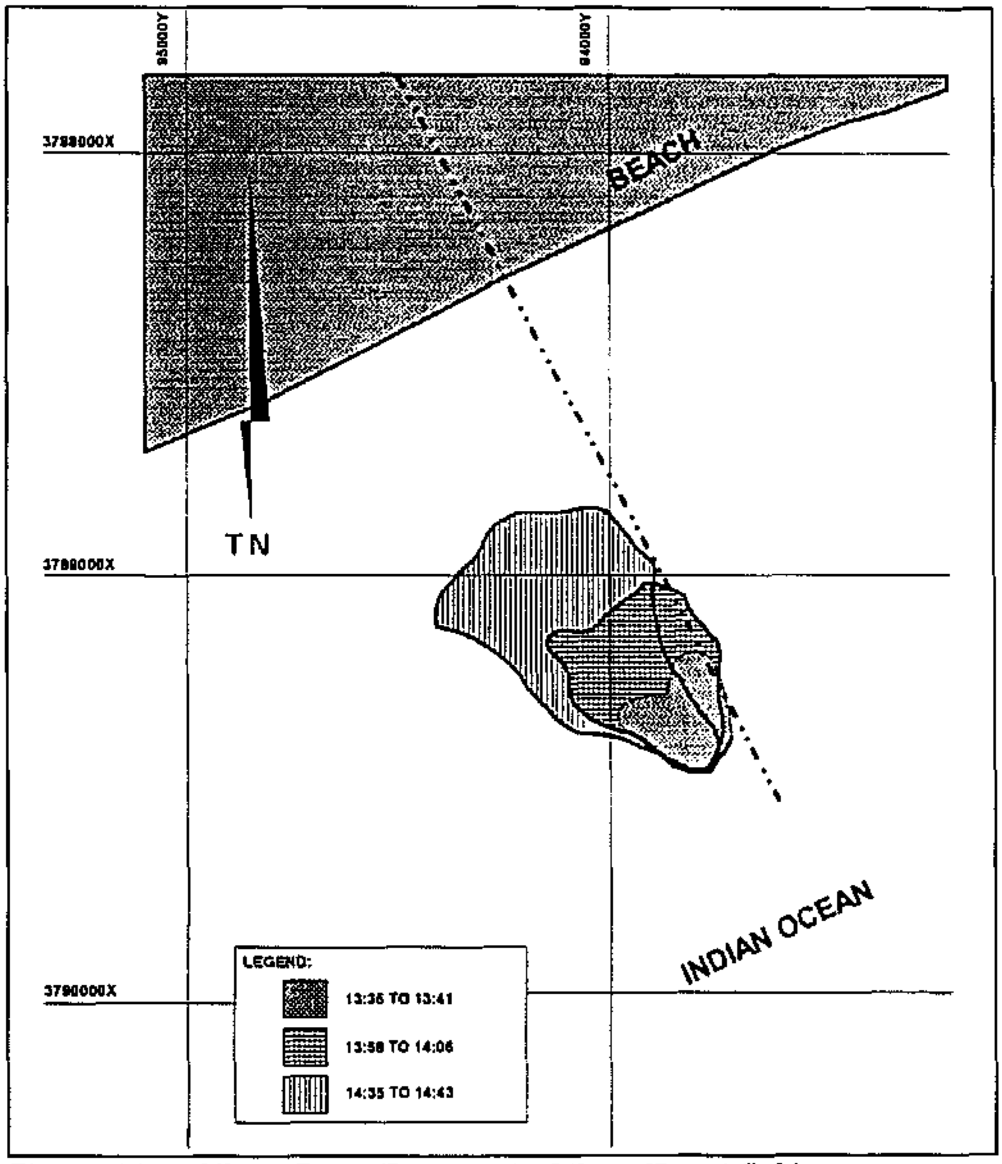

Figure 11a. Vlees Bay: Transport of the effluent field

Figure 11b. Vlees Bay: Transport of the effluent field

Samples were taken continuously while the effluent field was transected to determine the degree of secondary dilutions that could be achieved and the distribution of concentrations through the effluent field. The transects through the effluent field illustrating the measured concentrations are shown in Figure 11c.

The recorded achievable dilutions versus distance (straight line) from the discharge location (diffuser) are shown in Figure 11d. Dilutions of 1 000, 2 000 and 2 500 were achieved at approximately 130 *m*, 190 *m* and 3*50* m from the discharge location, respectively.

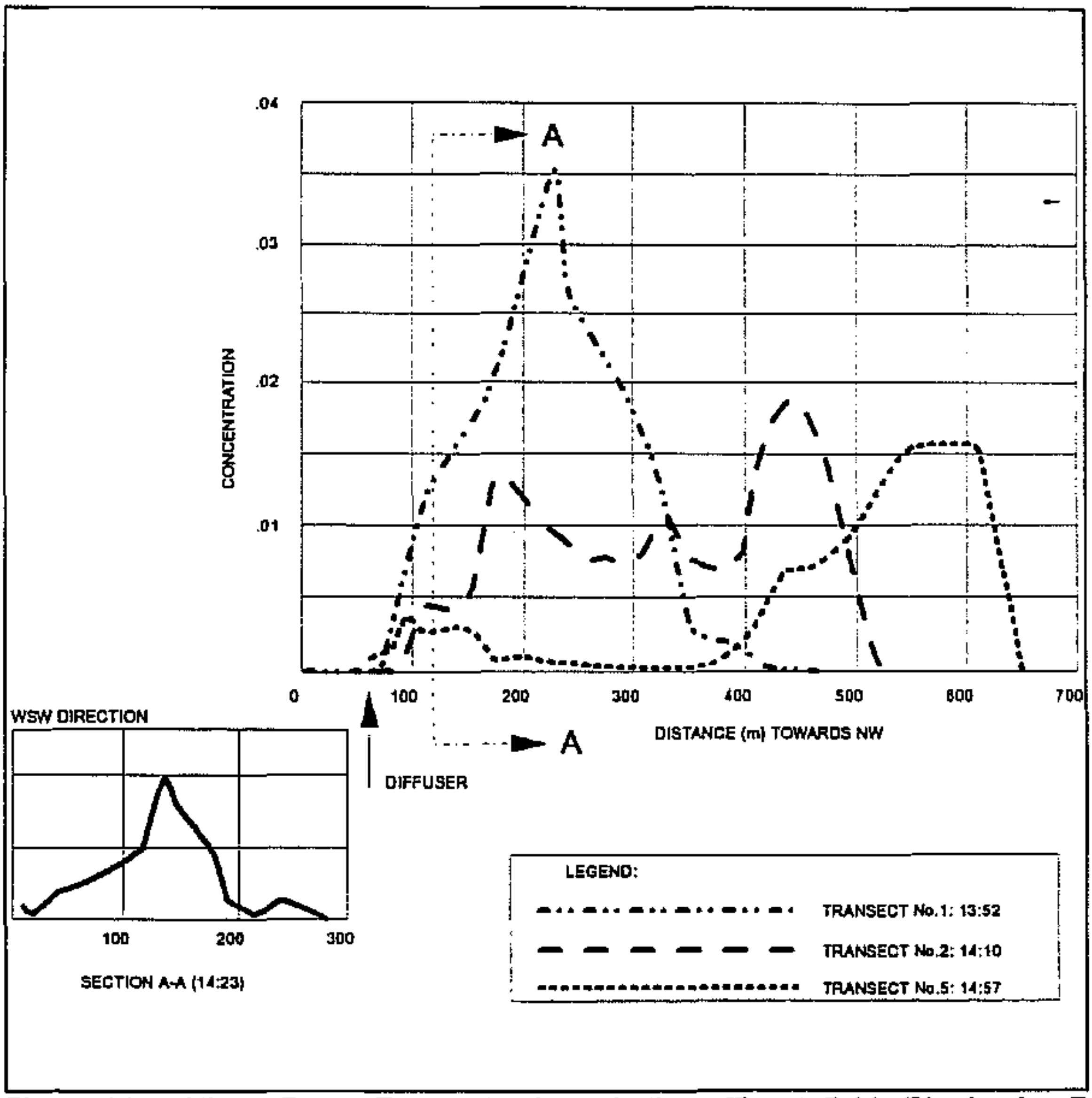

Figure 11c. Vlees Bay: Transects through the effluent field, Rhodamine-B concentrations

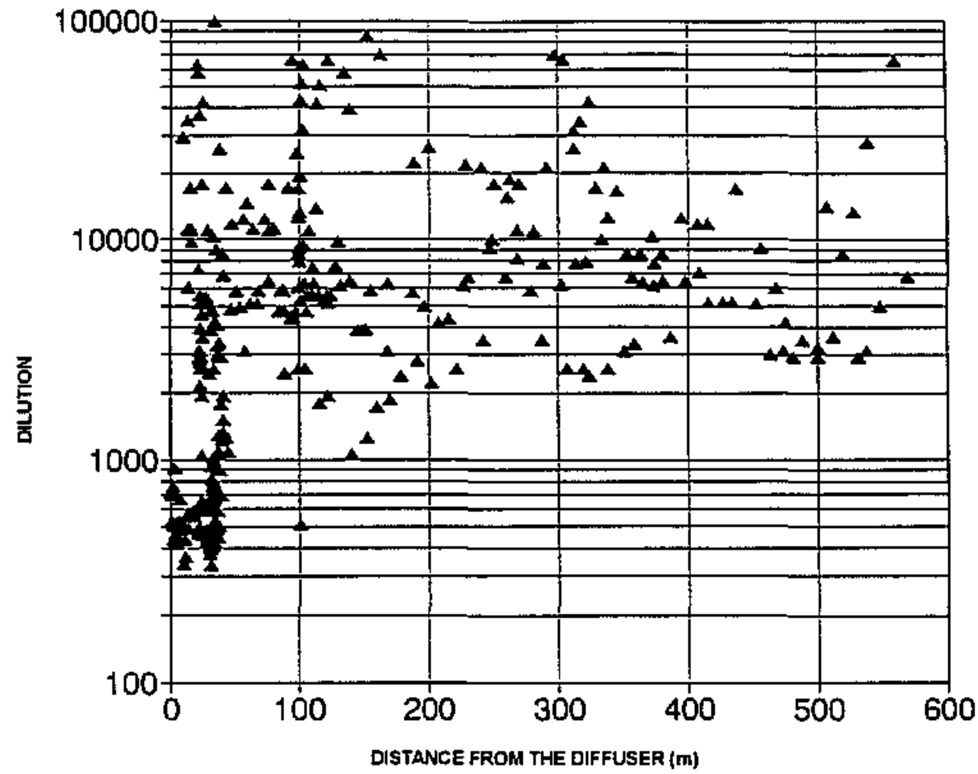

Figure 11d. Vlees Bay: Dilutions versus distance from the discharge location

4.2.3 Comparison of results

The comparison of the theoretical predictions according to Roberts (1977), EPA (1985) and WRc (1990) and the field dilutions measured on 10 November 1992 are shown in Table 14.

Table 14. Vlees Bay: Predicted dilutions versus measured dilutions

		MINIMUM	95 PERCENTILE	MEDIAN	MEAN
MEASURED		335	396	518	642
Stagnant Uniform	Roberts (1977) EPA (1985) WRc (1990)	164 194 -	220 260 265	* * 450	286 338 565
Current/ stratified	Wright (1984) EPA (1985) WRc (1990)	290-470 290-413 -	390-420 390-630 265	* * 450	506-546 520-820 565

* **Assumption: Gaussian distribution**

The comparison of the dilutions measured during actual conditions and those of the design criteria and the predicted dilutions for actual conditions are presented in Table 15.

Table 15. Vlees Bay: Comparison of dilutions measured during actual conditions and predicted dilutions for stagnant uniform and actual conditions

	MEASURED/PREDICTED (Stagnant Uniform)	MEASURED/PREDICTED (Moving water theory)
Roberts(1977):		
Minimum	2,0	NA
Mean	2,2	
EPA (1985):		
Minimum	1,7	0,7 - 1,2
Mean	1,9	0,7 - 1,2
WRc (1990):		
95 Percentile	1,5*	1,5*
Median	1,2*	1,2*
Mean	1,1*	1,1*
Wright (1984):		
Minimum		1,1-1,2
Mean	NA	1,2-1,3

* According to the WRc (1990) approach a buoyancy dominated condition (BDC) existed for which the theory for 'stagnant' conditions is applicable.

The predicted dilutions for actual conditions using the EPA (1985) model and WRc (1990) compared well with the measured dilutions.

4.3 Marine Outfall at Hout Bay

4.3.1 Predictions

The following data were used as input conditions:

Flow: 122,7 $l\ s^{-1}$

Density of effluent: 1000 $g\ l^{-1}$

Diffuser: 5 ports (diameter 100 *mm*)

4.3.1.1 Stagnant uniform theory

Table 16. Hout Bay: Predicted dilutions for stagnant uniform conditions

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Roberts (1977)	180	240	*	310
EPA (1985)	230	310	*	400
WRc (1990)	-	180	300	700

* Assumption: Gaussian distribution

4.3.1.2 Moving water theory

The EPA (1985) model and Wright (1984) were used to predict the dilutions for the actual conditions. Applying the WRc (1990) theory to the actual measured conditions, buoyancy dominated conditions (BDC) (stagnant water) existed.

The achievable dilutions for the pre- and post-discharge conditions as determined by the EPA (1985) model, Wright (1984) and WRc (1990) are shown in Table 17.

Table 17. Hout Bay: Predicted dilutions based on actual physical conditions measured on 12 October 1993

	MINIMUM	95 PERCENTILE	MEDIAN	MEAN
Wright (1984)	175-253	240-340	*	34-440
EPA (1985)	270-560	360-750	*	470-980
WRc (1990)	-	330	560	700

* Assumption: Gaussian distribution

The EPA (1985) model and Wright (1984) predicted the trapping of the effluent at a level between 6 *m* and 9 *m* below the surface due to a thermocline of approximately 1,3 °*C* at 10 *m* depth.

4.3.2 Field experiment

4.3.2.1 Weather and sea conditions

Table 18. Hout Bay: Weather and sea conditions on 12 October 1993

TIME			10:00	12:03	12:47	13:37
WIND:	Speed ($m\ s^{-1}$)		Calm			3
	Direction					270°
CURRENTS:						
	Surface:	Speed ($m\ s^{-1}$)			0,02	0,16
		Direction			344°	66°
	-5 *m*:	Speed($m\ s^{-1}$)			0,02	0,08
		Direction			152°	151°
	-10 *m*:	Speed ($m\ s^{-1}$)			0,02	0,11
		Direction			354°	89°
TEMPERATURE (°C):	Surface		13,97	14,60		
	- 5 *m*		12,88	12,81		
	- 10 *m*		11,53	11,63		
	- 15 *m*		11,34	10,47		
	- 20 *m*		10,73	10,54		
	- 25 *m*		10,58	10,33		
	- 30 *m*		10,30	10,24		
	- 35 *m*		10,25	10,26		
SALINITY :	Surface		34,80	34,82		
	- 5 *m*		34,80	34,68		
	- 10 *m*		34,63	34,62		
	- 15 *m*		34,60	34,46		
	- 20 *m*		34,55	34,40		
	- 25 *m*		34,50	34,49		
	- 30 *m*		34,45	34,43		
	- 35 *m*		34,42	34,42		

Physical conditions represented almost 'stagnant' conditions (0,02 $m\ s^{-1}$ currents) before the effluent plume surfaced. A slight westerly wind caused an increase in current speeds later in the day. Except for a 1 °C increase in surface temperatures, the temperatures and salinities remained almost constant throughout the depth of the water column. The current measured at the surface and sub-surface are illustrated in Figure 12.

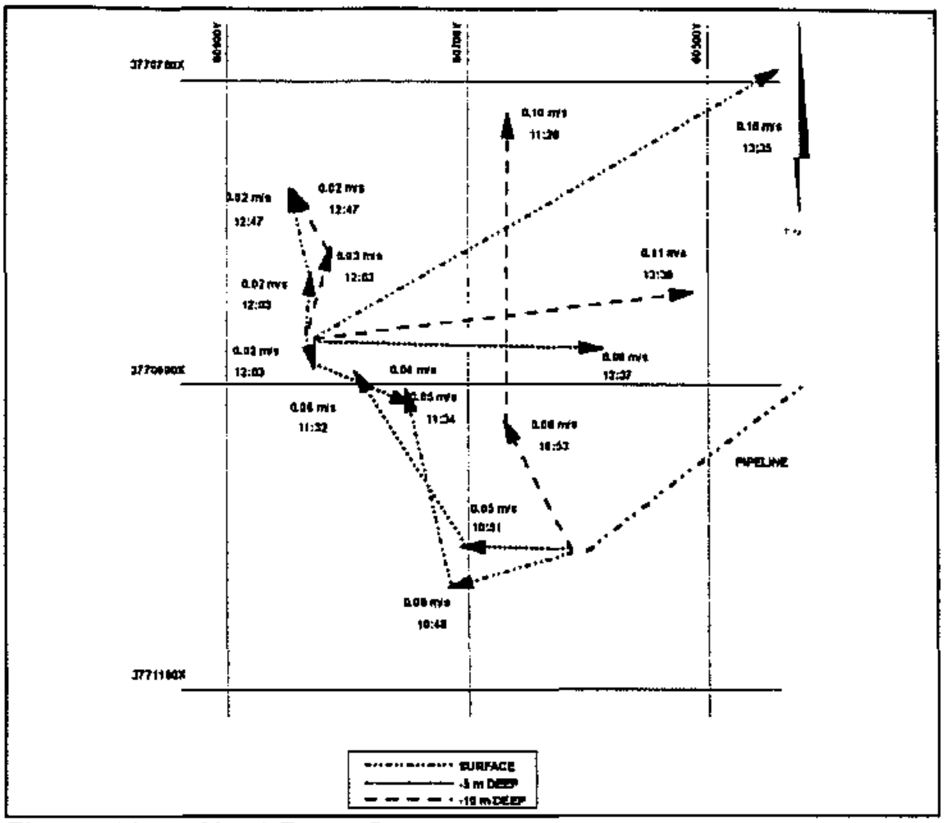

Figure 12. Hout Bay: Currents

4.3.2.2 Specific details on dye release

Table 19. Hout Bay: Details on the dye release on 12 October 1993

INJECTION:	
Volume of Rhodamine (*l*)	33
Pre-dilution	155
Total volume of dye (*l*)	165
Time of release	12:05
Duration of release (*s*)	690
Gravity discharge rate ($l\ s^{-1}$)	122,7
Average concentration at input ($mg\ l^{-1}$)	571
Time of surfacing	12:42
Travel time (*min*)	37
AT THE DIFFUSER:	
Highest concentration ($mg\ l^{-1}$)	660
2nd highest concentration ($mg\ l^{-1}$)	590
Average from 12:42 to 12:50 ($mg\ l^{-1}$)	372

The average concentration at the treatment works was 571 $mg\ l^{-1}$ compared to an average of 371 $mg\ l^{-1}$ at the diffuser. However, as the dye did not pass through any pumps (gravity discharge), the samples at the treatment works could reflect high concentrations due to insufficient mixing over less than 10 m after the release. The measured concentrations at the treatment works (downstream of the release point) and in the diffuser are illustrated in Figure 13.

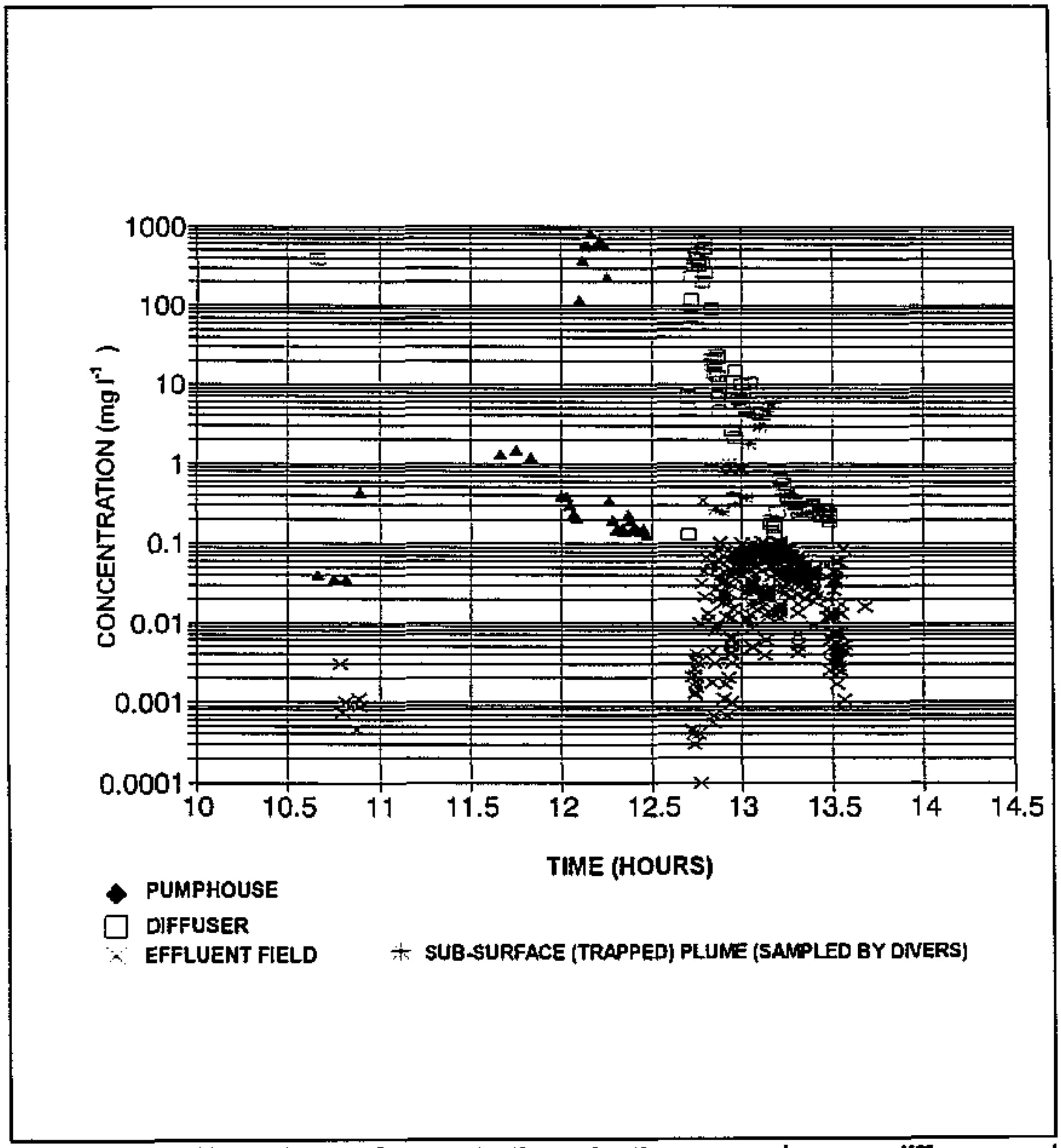

Figure 13. Hout Bay: Concentrations in the pump house, diffuser and effluent field

4.3.2.3 Measured initial dilutions

The measured initial concentrations (134 samples) at the surface (Figure 14) during the initial dilution process (that is between 12:42 and 13:33 and within 80 *m* from the diffuser) yielded mean, median and 95 percentile dilutions of 8 000, 6 890 and 4 043, respectively (standard deviation of 3 596). These high dilutions on the surface were due to the trapping of the effluent field approximately 10 *m* below the surface. These dilutions must not be considered as the achievable initial dilutions. The results are only given to illustrate the high degree of surface dilutions which can be achieved even if the effluent plume is clearly visible.

Divers retrieved 34 samples from the trapped effluent field. The measured dilution were 640, 460 and 120 for the mean, median and 95 percentile values, respectively (standard deviation of 452). The statistical representation of these samples cannot be verified due to the limited number of samples and the lack of accurate time and position recordings. Because the visibility was extremely good, it was possible for the divers to detect clearly the sub-surface 'boil' from which the samples were collected. These measured dilutions will therefore be conditionally used for comparison with the predicted dilutions.

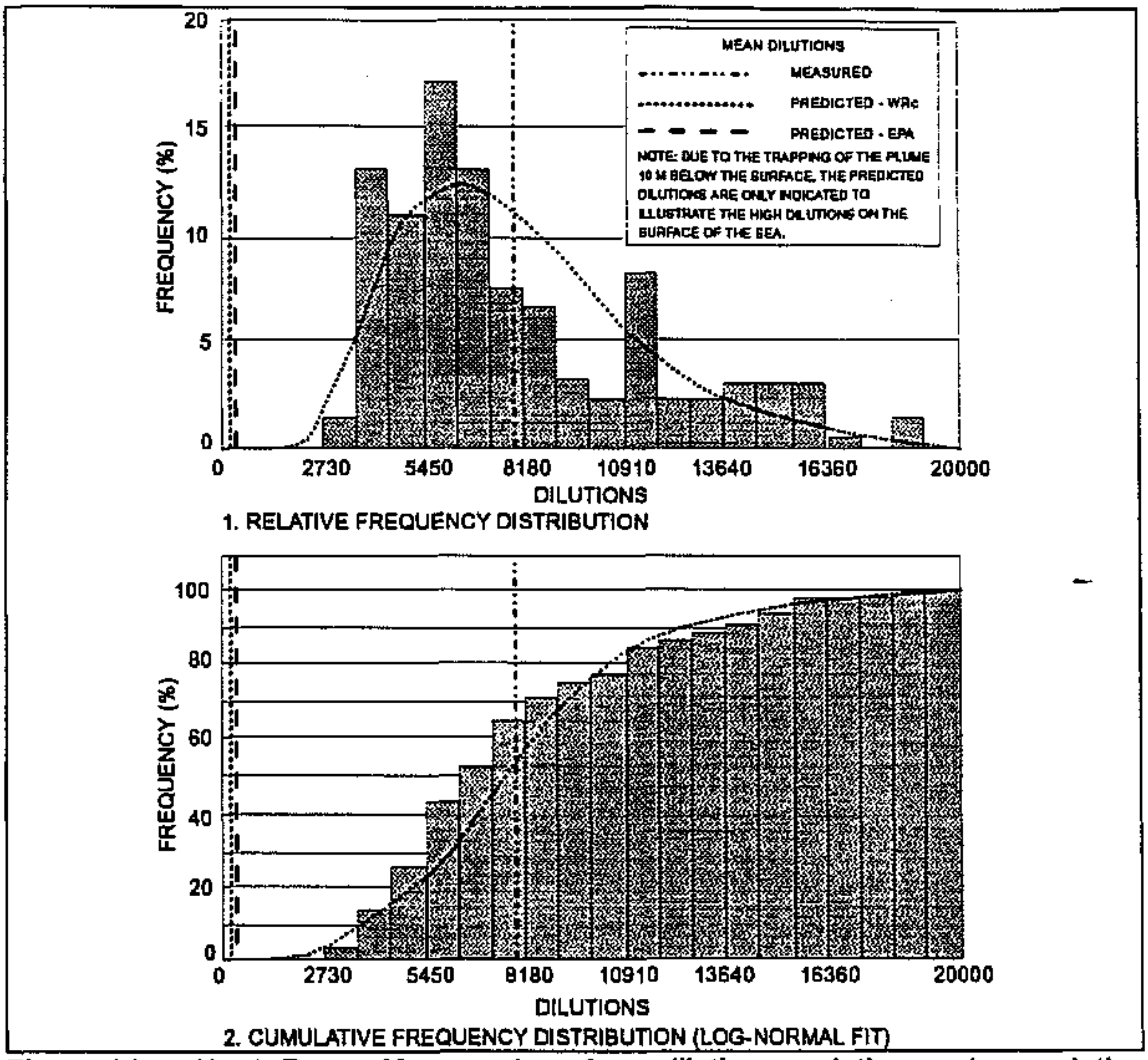

Figure 14. Hout Bay: Measured surface dilutions, relative and cumulative frequencies

4.3.2.4 Transport and secondary dilutions

The growth of the effluent surface field was recorded on three occasions by circumnavigation and accurate position fixing. Photos were taken from the shore (elevation 330 *m*), but due to the trapping of the plume and the high surface dilutions, definition was lost soon after the surfacing of the dye. Due to weak currents (0,02 $m\ s^{-1}$ to a maximum of 0,16 $m\ s^{-1}$) the effluent field did not move away from the discharge location, but grew in size at the discharge location as illustrated in Figure 15a.

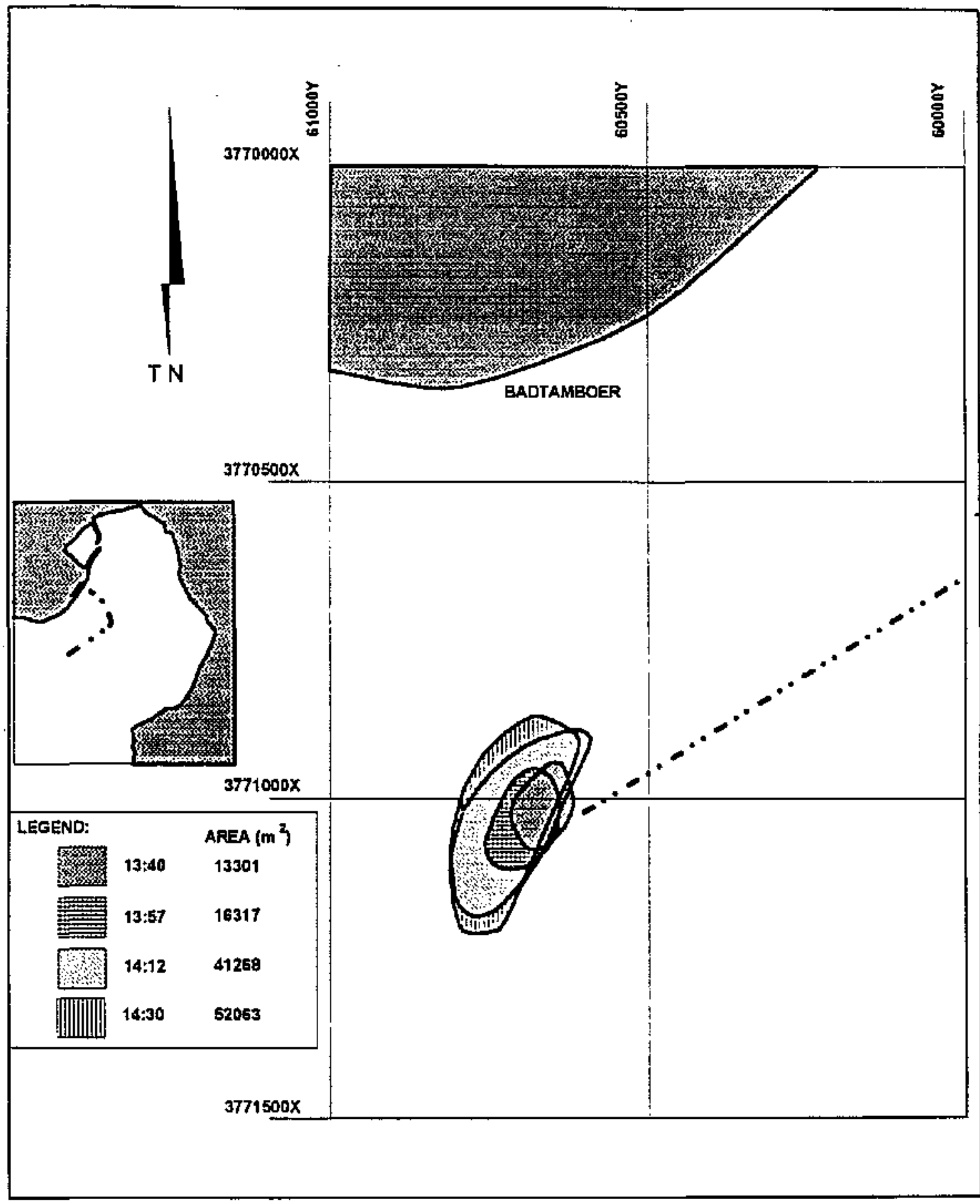

Figure 15a. Hout Bay: Transport of the effluent field

The recorded surface dilutions versus distance from the diffuser are illustrated in Figure 15b. Up to a distance of 200 *m* away from the diffuser the secondary dilutions for the surface field are almost negligible as can be seen in the figure.

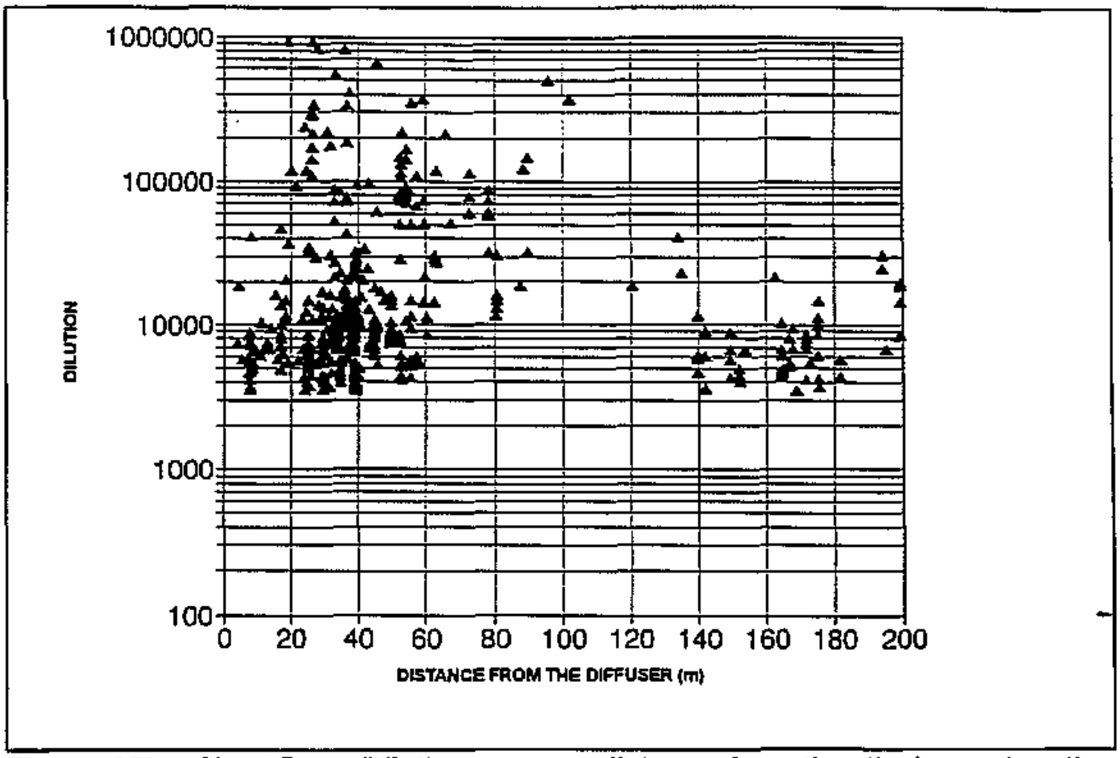

Figure 15b. Hout Bay: Dilutions versus distance from the discharge location

4.3.3 Comparison of results

Table 20. Hout Bay: Predicted dilutions versus measured dilutions

		MINIMUM	95 PERCENTILE	MEDIAN	MEAN
MEASURED		120**	120	460	640
Stagnant Uniform	Roberts (1977)	180	240	*	310
	EPA (1985)	230	310	*	400
	WRc (1990)	-	330	560	700
Current/ stratified	Wright (1984)	175-253	240-340	*	304-440
	EPA (1985)	270-560	360-750	*	470-980
	WRc (1990)	-	330	560	565

* Assumption: Gaussian distribution

** A very high concentration resulting in a dilution of only 120 was recorded. It is expected that this high concentration could be due to a sample which was collected below the 'boil' (in the rising plume), as orientation was not easy. However, the validity (or not) of this value cannot be proved and is therefore included. When mean values are compared to predicted dilutions it seemed that this high concentration was not realistic.

The comparison of the dilutions measured during actual conditions with that of stagnant uniform conditions and the predicted dilutions for actual conditions are presented in Table 21.

Table 21. Hout Bay: Comparison of dilutions measured during actual conditions and predicted dilutions for stagnant uniform and actual conditions

	MEASURED/PREDICTED (Stagnant Uniform)	MEASURED/PREDICTED (Moving water theory)
Roberts(1977):		
Minimum	0,4	NA
Mean	2,1	
EPA (1985):		
Minimum	0,3	0,1 - 0,3
Mean	1,6	0,7 - 1,4
WRc (1990):		
95 Percentile	0,4	0,4
Median	0,8	0,8
Mean	0,9	0,9
Wright (1984):		
Minimum		0,5 - 0,7
Mean	-	1,5 - 2,1

Although the samples taken by the divers cannot be considered or verified as representative, the ratio of the measured and the predicted mean dilution is close to unity, i.e. 0,7 to 1,4 for the EPA (1985) model, 1,5 to 2,1 according to Wright (1984) and 0,9 by using the WRc (1990) approach.

Surface dilutions were more than 12 times the initial dilutions measured in the trapped 'boil' approximately 10 *m* below the surface. This indicates that although a plume may be visible, concentrations could be reduced to very low levels under certain conditions. The transport of the mean effluent field (trapped) may also be completely different to the transport of the visible surface field, especially during strong wind conditions.

4.4 Summary

The three study areas, Richards Bay, Vlees Bay and Hout Bay, were chosen to represent the different South African coastal conditions and the various type of deep sea outfalls in South Africa.

The same methodology was adopted for the three outfalls. Rhodamine-B was pre-diluted and released at the headworks. Samples were taken at the headworks downstream of the release point, at the diffuser (by divers or by pipe to the sea-surface) and in the effluent 'boil' at the sea-surface to determine the initial dilutions as well as in the moving effluent field. Where the effluent was trapped below the surface at Hout Bay, divers took samples in the sub-surface 'boil'.

The ratios of the measured and predicted dilutions for the three experiments are summarized in Table 22. Because the *stagnant uniform* concept had previously been applied in the Richards Bay outfall design, these figures are also summarized in Table 22, indicating under-predictions by a factor of more than six in a dynamic receiving environment.

Table 22: Summary Table: Measured versus predicted dilutions

	MEASURED/PREDICTED STAGNANT UNIFORM			MEASURED/PREDICTED ACTUAL CONDITIONS			
	Richards Bay	Vlees Bay	Hout Bay	Richards Bay	Vlees Bay	Hout Bay	Combined
Roberts (1977) Minimum Mean	 7,5 11,3	 2,0 2,2	 0,4 2,1	NA	NA	NA	NA
EPA (1985) Minimum Mean	 6,0 9,0	 1,7 1,9	 0,3 1,6	 1,1 1,6	 0,7-1,2 0,7-1,2	 0,1-0,3 0,7-1,4	 0,75 1,20
WRc (1990) 95 Percentile Median Mean	 5,2 6,3 5,6	 1,5 1,2 1,1	 0,4 0,8 0,9	 1,3 1,0 1,0	 1,5 1,2 1,1	 0,4 0,8 0,9	 1,1 1,0 1,0
Wright (1984) Minimum Mean	-	-	-	 1,0 1,5	 1,1-1,2 1,2-1,3	 0,5-0,7 1,5-2,1	 0,9 1,5

At *near stagnant* conditions when the effluent plume surfaced (Vlees Bay) the under-prediction by a factor of approximately two corresponds with the finding of Toms and Botes (1984). For the Hout Bay experiment where the effluent plume was trapped due to stratification, the predicted minimum dilutions were over-estimated. However, the representativeness of these samples could not be proven statistically due to the complicated sampling procedures and the limited number of samples.

Predicted dilutions where actual conditions (currents and stratification) were used as input conditions, compared well with the measured dilutions, according to the EPA (1985) program, Wright (1984) or by following the WRc (1990) approach (Figure16).

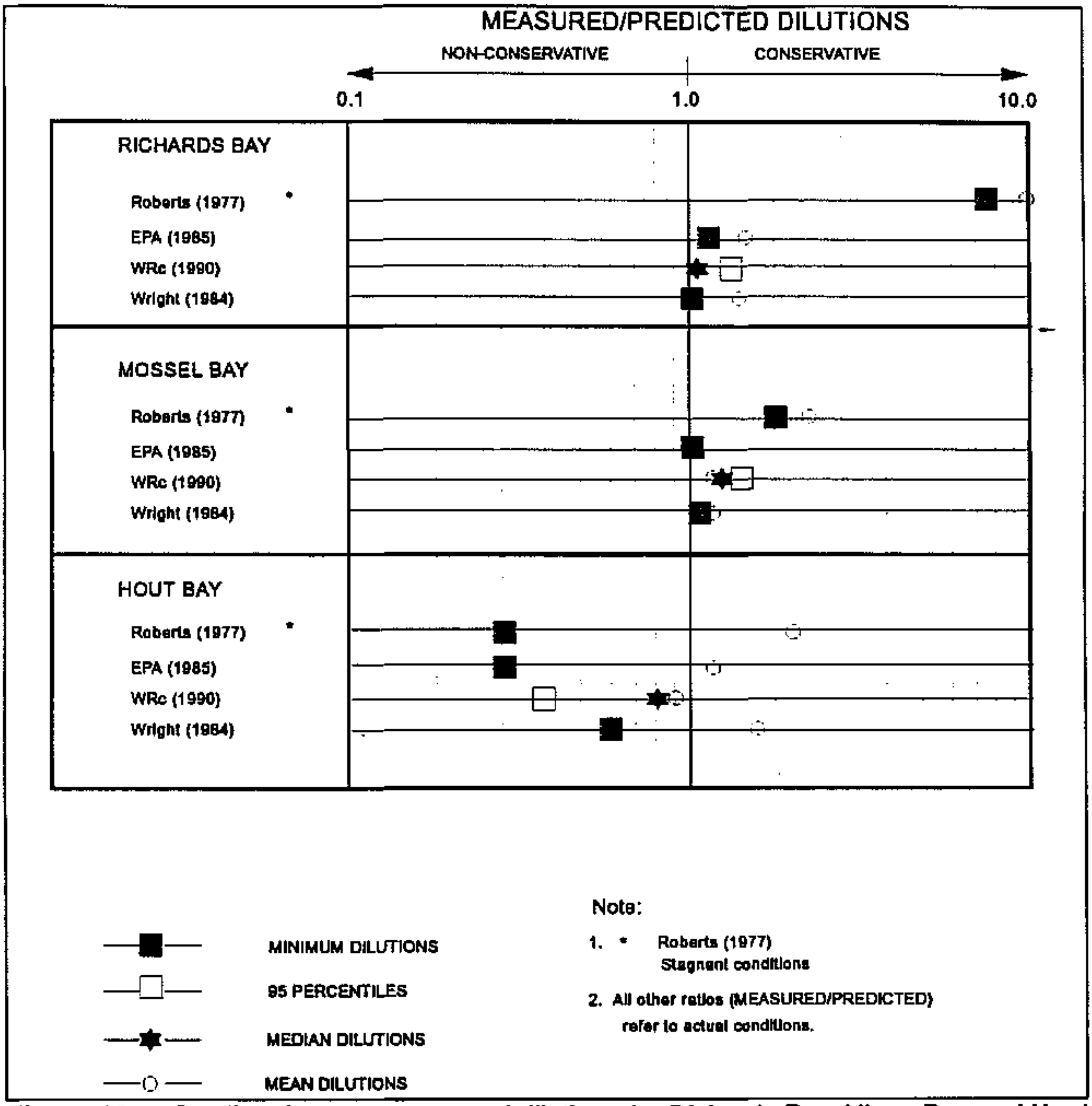

Figure 16. Predicted versus measured dilutions for Richards Bay, Vlees Bay and Hout Bay

5. CONCLUSIONS AND RECOMMENDATIONS

Field Experiment

5.1 The three field experiments for completely different outfall systems in various physical/weather conditions, indicated that the technique used in these studies (dye release) can confidently be applied to check the performance of any outfall system if the effluent is buoyant and not trapped below the surface as a result of stratification in the water column. From these experiments it was shown that the degree of absorption of the dye in the pipeline when the effluent is dosed at the headworks can be neglected. This implies that it is not necessary to use divers for sampling at the diffusers, which, in turn, makes these experiments less dependent on the weather.

For a trapped effluent field, additional fluorometric equipment (profiler) should be acquired, for direct recordings throughout the depth.

5.2 For the commissioning of a new outfall a field experiment contributes to the understanding of the hydraulic behaviour (port flows, total headlosses due to friction, discharge rates, etc.) and provides practical verification of the entire discharge process.

5.3 From these field experiments it was found that the photographic recording of an effluent field is not practical due to the unpredictable weather conditions (poor visibility) and high dilutions (not enough contrast).

Statistical Analysis of Data

5.4 From previous field tests (Toms and Botes, 1987) the concepts 'minimum' and 'average' dilutions could not be defined properly and determined for the field tests. A conservative approach was followed by assuming the 'average' dilution refers to the highest concentration that could be detected.

With (a) the experience gained by Toms and Botes (1987), (b) the results obtained from the present series of field tests and (c) the approach followed by WRc (1990) (i.e., to consider more statistical parameters such as 95 percentiles, mean and median values for a typical frequency distribution curve for achievable dilutions) a more realistic approach was followed for this project by comparing similar statistical parameters for the predicted and measured dilutions.

Stagnant Uniform Theory

5.5 To apply a 'stagnant uniform' theory to a dynamic receiving environment is not a realistic approach as the dilutions will be under-estimated by a factor of more than six if ambient current speeds exceed 30 $cm\ s^{-1}$, irrespective of the theory which is used (refer to Richards Bay).

Ambient Conditions (Moving Water Theory)

5.6 When taking the ambient conditions into account the predicted dilutions according to EPA (1985), Wright (1984) and WRc (1990) compared well with the measured dilutions, although the EPA (1985) model and Wright (1984) provide a slightly more conservative prediction when considering mean dilution values. Considering the simplicity of the technique, the approach followed by WRc (1990) compares extremely well with the prototype measurements.

5.7 Numerous theories and models are available to predict the initial dilutions which can be achieved when a buoyant effluent is discharged to sea via a deep sea outfall. The choice of the technique to be applied is to be decided by the design engineer and must be agreed upon by the client and the control authority. No single theory or technique available can be considered as inaccurate as these were not developed in isolation. It is not practical to apply numerous techniques for each and every study or design. The essential issue is that the technique applied should be considered reliable and the engineer should be aware of the sensitivity of the prediction to the diversity of physical conditions off the South

African coast. Confidence in the theoretical prediction can only be gained by comparing the predicted values to actual achievable dilutions under various physical conditions.

With regard to this aspect the three field experiments together with the field experiment conducted at Camps Bay in 1984 (Toms and Botes, 1984) were extremely valuable, not only for the researchers of this study, but for the entire engineering and scientific community involved in the design and assessment of sea outfalls and marine water quality in South Africa.

The more sophisticated techniques provide more accurate predictions. However, the more detailed the output the more detailed the input that is required. Taking the diversity and complexity of the South African coastline into account, the acquisition of data required for model inputs is extremely expensive in terms of manpower, sophisticated equipment and operational expenses.

With this study it was proved that by using a fairly simple technique developed by the WRc (1990) the overall predictions are as accurate as the prediction by more sophisticated methods. This does not mean that more sophisticated models are not necessary, as for specific applications more details on the behaviour of a rising plume may be required. When extensive data sets are not available more simple techniques can be applied with confidence, especially when followed up by a few field experiments to determine the actual achievable dilutions.

Recommendations

5.8 Secondary dilutions are limited to approximately five times within the first 200 *m* from the 'boil' whereafter only another two times dilution can be expected even as far as one kilometre away from the discharge location. It is strongly recommended that the available techniques, both analytical and numerical (models), be applied to the data available from these experiments in order to prove and gain similar confidence as for the prediction of initial dilutions. The ultimate concentrations at the target locations are controlled by (a) the hydraulic performance of the outfall for the achievement of the required initial dilutions (controlled process) and (b) by the physical transport and decay of non-conservative variables, for example microbial organisms, which is an uncontrolled process which depends on nature. It will be extremely useful if a number of field experiments can be conducted where the measurement of the physical dilutions are combined with the decay of microbial organisms as these two processes determine the ultimate location of the outfall site. Research in South Africa on the decay of microbial organisms and the transport/dispersion of a effluent field are limited.

Sophisticated numerical models to simulate the transport of an effluent field including the decay of microbial organisms, are available, but need to be evaluated under actual South African conditions.

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Dr D van Driel	Department of Water Affairs and Forestry
Mr H Schoeman	Mossgas
Mr R K Mitchell	Werstern Cape Regional Services Council

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