

SOUTHERN SEAWATER DESALINATION PLANT - MARINE INVESTIGATIONS

Near-field Analysis and Diffuser Design

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KBR derived the data in this report primarily from field monitoring and modelling analyses. The passage of time, manifestation of latent conditions or impacts of future events may require further exploration at the site and subsequent data analysis, and re-evaluation of the findings, observations and conclusions expressed in this report.

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Revision History

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1 Introduction

The Water Corporation of Western Australia is progressing with the development of the Southern Seawater Desalination Plant (SSDP) located to the north of Binningup, Western Australia.

The SSDP has been selected as the preferred option to ultimately produce 100 GL/a of drinking water to meet the forecasted increase in demand. The plant will require the construction of a marine inlet to source influent seawater and an outlet to dispose of the brine reject.

Kellogg Brown and Root Pty Ltd (KBR) were engaged by the Water Corporation to undertake a preliminary diffuser design for the SSDP outfall.

2 Design Methodology

2.1 MIXING AND DISPERSION OF DENSE PLUMES

Dispersion of outfall plumes is governed by the physical characteristics of the diffuser design as well as oceanographic conditions of the discharge environment. Due to the different governing physical processes, mixing and dispersion of outfall plumes is classed into near-field mixing and far-field mixing.

Near-field mixing is achieved predominantly by the momentum flux of the discharge velocity, which induces entrainment of the surrounding ambient fluid, coupled with additional forces from currents in the receiving waters. Far-field mixing and dilution rely purely on the natural processes of winds and waves inducing turbulent mixing.

Unlike a positively buoyant plume, which will rise to the surface, denser (negatively buoyant) brine plume will sink to the bottom of the sea bed. While both plumes will undergo similar near-field mixing processes of entrainment induced by momentum flux, buoyant plumes experience more mixing in the far-field than dense plumes, as buoyant plumes ultimately reside at the surface where the actions of turbulent mixing due to winds and waves are more pronounced.

At the far-field, dense plumes are at the sea bed where mixing occurs only due to bed velocities, baroclinic flows and turbulent mixing down from the surface, which are typically less energetic than the processes closer to the surface. Therefore, it is important that diffuser designs for outfalls focus on achieving the best possible dilution in the near-field and not rely on far-field dilution.

2.2 DESIGN TOOLS

The two tools used for the preliminary diffuser design and analysis of near-field mixing are:

- Empirical relationships by Roberts et al. (1997); and
- *Visual Plumes* software developed by the US EPA (Frick et al., 2001).

2.2.1 Roberts empirical relationships

The empirical relationships developed by Roberts et al. (1997) have been widely applied to diffuser design and near-field mixing analysis of dense plumes. The characteristic of a dense jet exiting the diffuser nozzle depicted by Roberts et al. (1997) is shown in Figure 2.1.

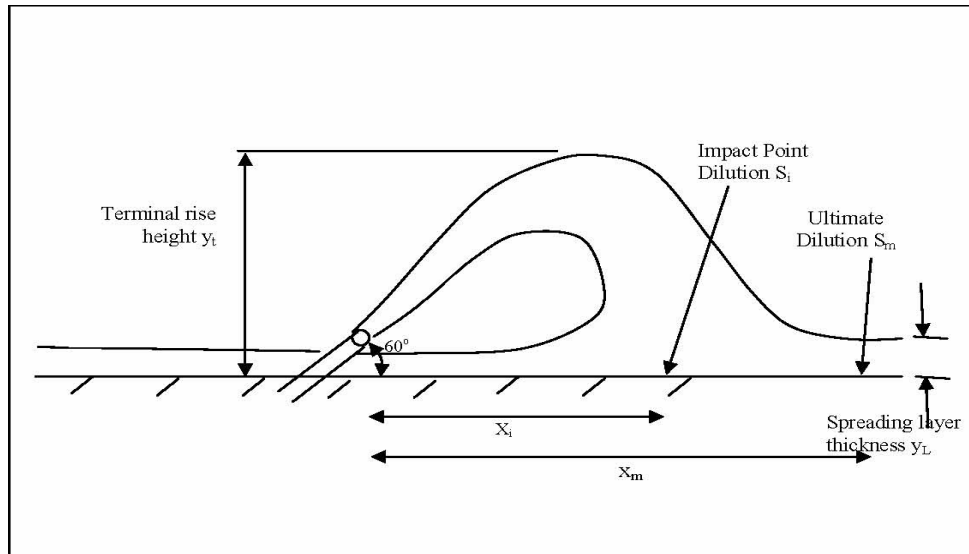


Figure 2.1 - Dense Jet Characteristics (after Roberts et al., 1997)

The following empirical relationships were developed by Roberts et al. (1997) which expressed the plume characteristics in terms of nozzle diameter and the jet densimetric Froude number:

$$y_t = 2.2dFr$$

$$x_m = 9.0dFr$$

$$S_i = 1.6Fr$$

$$y_L = 0.7dFr$$

$$S_m = 2.6Fr$$

$$Fr = u / \{ [g(\rho - \rho_a) / \rho_a] d \}^{1/2}$$

$$x_i = 2.4dFr$$

Where:

y_t = terminal rise height

g = acceleration due to gravity

S_i = impact point dilution

Fr = densimetric Froude number

S_m = ultimate minimum dilution

ρ = density of discharge

x_m = location of end of near-field region

ρ_a = ambient density

x_i = location of impact point

u = jet velocity

y_L = thickness of bottom layer

Roberts et al. (1997) derived these relationships through experimental work using sophisticated laser-induced fluorescence techniques as well as micro-conductivity probes to determine dilutions of the jet plume.

The above empirical relationships are specific for a diffuser angle at 60° from the horizontal. Roberts et al. (1997) established that 60° from the horizontal is the preferred diffuser design angle as it provides the longest trajectory of the plume, and hence the maximum dilution, before it reaches the ocean floor.

The Centre for Water Research (University of Western Australia) undertook a field study to verify performance of the outlet for the existing desalination plant discharging into Cockburn Sound (CWR, 2007). This fieldwork identified that whilst the relationship by Roberts et al. (1997) is valid for Froude numbers higher than 20, it underestimates dilutions for Froude numbers lower than 20.

Roberts et al. (1997) empirical relationships have been incorporated into a purpose-made EXCEL spreadsheet (refer Appendix A) to facilitate the evaluation of various diffuser alternatives.

2.2.2 Visual Plumes

The *Visual Plumes* analysis requires the following inputs for computation of the plume trajectory and dilution:

- Diffuser angle;
- Diffuser diameter;
- Water depth;
- Number of ports and port spacings;
- Discharge temperature and salinity;
- Ambient temperature and salinity with varying depth;
- Ambient ocean currents with depth.

The *Visual Plumes* design and mixing analysis is an iterative process, where model simulations are repeated for a combination of the above listed variables. The limitation to *Visual Plumes* analysis for dense plumes is that the model does not recognise when the dense plume hits the ocean floor. For this reason, predictions by the model beyond the impact point are not reliable.

Consequently, the use of *Visual Plumes* within this diffuser design analysis is for the sole purpose of cross-checking plume characteristics calculated using Roberts's empirical relationships.

2.3 ENVIRONMENTAL DESIGN CRITERIA

In absence of established environmental criteria for Binningup coastal waters, advice from the Water Corporation has been used as a basis for design of the diffuser:

Water Corporation criteria:

- The salinity level beyond the edge of the near-field mixing zone is not to exceed 1 ppt above ambient salinity levels

KBR's water quality monitoring program (KBR, 2007) has recorded ambient salinity levels averaging 36 ppt and therefore this has been applied as the ambient salinity level for Binningup coastal waters.

Therefore the salinity level beyond the edge of the near-field mixing zone is not to exceed 37 ppt.

3 Assumptions and Conditions

Prior to carrying out the near-field analysis to determine a suitable diffuser design, a number of assumptions and conditions were established:

3.1 RECOVERY RATE

The recovery rate (i.e. ratio of produced potable water versus intake of seawater) of the plant is expected to be in the range of 41-45%.

Depending on this recovery rate, the brine discharge rate and the associated brine concentrations can vary. A recovery rate of 42% (advised by the plant designers to be the most likely case) leads to more favourable marine conditions than a recovery rate of 45% as it produces (for the same outfall geometry), higher dilution and accordingly a lower salinity difference between the diluted brine and ambient seawater.

A recovery rate of 45% has been applied for the nominal diffuser design as it generates a more conservative dilution value.

3.2 SALINITY OF AMBIENT SEAWATER

Based on field data collected by KBR (KBR, 2007), ambient seawater in the Binningup coastal region has an average salinity of 36 ppt.

3.3 TEMPERATURE AND DENSITY OF AMBIENT SEAWATER

Based on field data collected by KBR (KBR, 2007), seawater temperature in the Binningup coastal region varies seasonally (i.e. between 15°C and 25°C).

For the nominal diffuser design, a temperature of 18°C and a density of 1025.27 kg/m³ has been applied.

3.4 SALINITY OF RETURN BRINE

Based on a recovery rate of 45%, a return brine salinity of 65.45 ppt has been calculated and applied for dilution calculations.

3.5 TEMPERATURE AND DENSITY OF RETURN BRINE

It is expected that the reverse osmosis process will increase the temperature of the return brine by ~2°C, resulting in a temperature of 20°C and density of 1048.21 kg/m³.

3.6 TWO PHASES OF SSDP OPERATION

The SSDP will be constructed in two phases; initially producing 50 GL/a drinking water; ramping up to ultimately produce 100 GL/a.

During the first phase of operation (i.e. whilst the plant is producing 50 GL/a of drinking water) the diffuser will be operating with half of the ports open. By having 50% of the ports open, combined with 50% total drinking water production (i.e. 50 GL/a), the exact same dilution will be achieved as having 100% ports open and full drinking water capacity (i.e. 100 GL/a).

3.7 OPERATIONAL DAYS PER YEAR

To allow for annual maintenance of the facilities, the nominal production period is 330 days per year.

3.8 RANGE OF FLOW CONDITIONS

The near-field analysis was undertaken over a range of flow conditions shown below in Table 3.1.

Table 3.1 - Range of Flow Conditions analysed

Case	Potable Water Production	Note
Q_{Peak}	115 GL/a	Peak flow rate
Q_{Design}	100 GL/a	Design flow rate
$\frac{2}{3} Q_{\text{Design}}$	66.6 GL/a	Typical flow rate

4 Diffuser Geometry

4.1 DESIGN REQUIREMENTS

The diffuser geometry was designed to meet the following design requirements:

- Ensure that the discharge plume is fully submerged (i.e. terminal rise height \ll ocean water surface i.e. ~ 11 m.)
- Ensure that the salinity level beyond the edge of the near-field mixing zone is not more than 1 ppt above ambient salinity (i.e. ≤ 37 ppt)

The optimal diffuser designed geometry to meet the above requirements is listed below in Table 4.1.

Table 4.1 - Geometry of proposed diffuser design

Design feature	Value
Diffuser port diameter (mm)	140
Spacing of ports (m)	5
Number of ports (spaced on one side)	88
Vertical angle from the horizontal (°)	60
Diffuser port depth (m)	11.0
Length of diffuser (m)	440
Length of outlet pipeline up to the diffuser (m)	600

4.2 HYDRAULIC ARRANGEMENT

The ultimate diffuser arrangement will depend on acceptable hydraulic losses through the outlet pipe.

Revision of the diffuser design may be required at the detailed engineering design phase to meet the chosen hydraulic arrangement.

4.3 PLUME CHARACTERISTICS FROM ROBERTS EMPIRICAL FORMULA

Roberts et al. (1997) formula was applied to the diffuser design outlined above for the three flow cases.

The resulting plume characteristics are shown in Table 4.2 and Figure 4.1 over page (refer to Appendix A for excel spreadsheet)

Table 4.2 - Plume characteristics predicted by Roberts formula

Case	Potable Water Production (GL/a)	Resultant Brine Production (ML/day)	Resultant Brine Production (m ³ /s)	Froude Number	Terminal Rise Height (m)	Distance to end of near-field (m)	Dilution at the end of near-field	Δ S at the end of near-field (ppt) [Ambient 36 ppt]	Spreading Layer Thickness (m)
Q _{Peak}	115	425.9	4.93	20.8	6.4	26.2	54	0.55	2.0
Q _{Design}	100	370.4	4.29	18.1	5.6	22.8	47	0.63	1.8
2/3 Q _{Design}	66.6	246.9	2.86	12.0	3.7	15.3	31	0.94	1.2

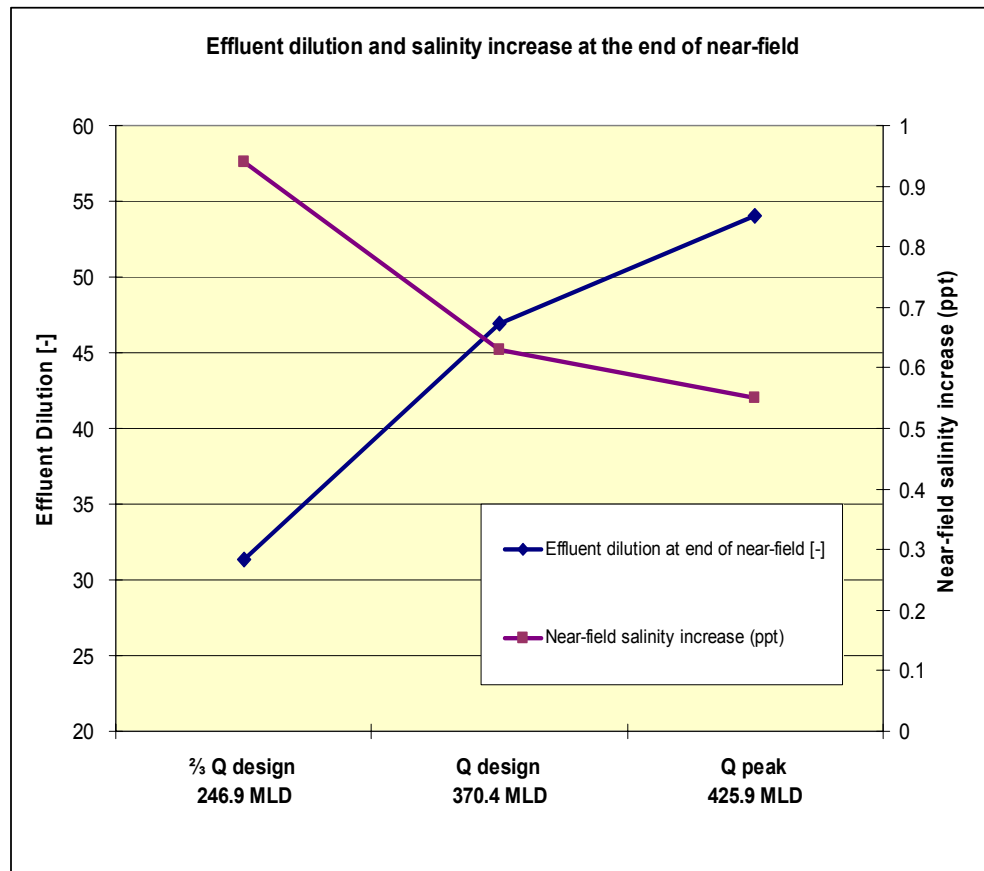


Figure 4.1 - Effluent dilution and salinity increase at the end of near-field

Figure 4.2 below shows the estimate brine dilution for the Q_{Peak} brine discharge flow rate (based upon Roberts and Sternau (1997) methodology).

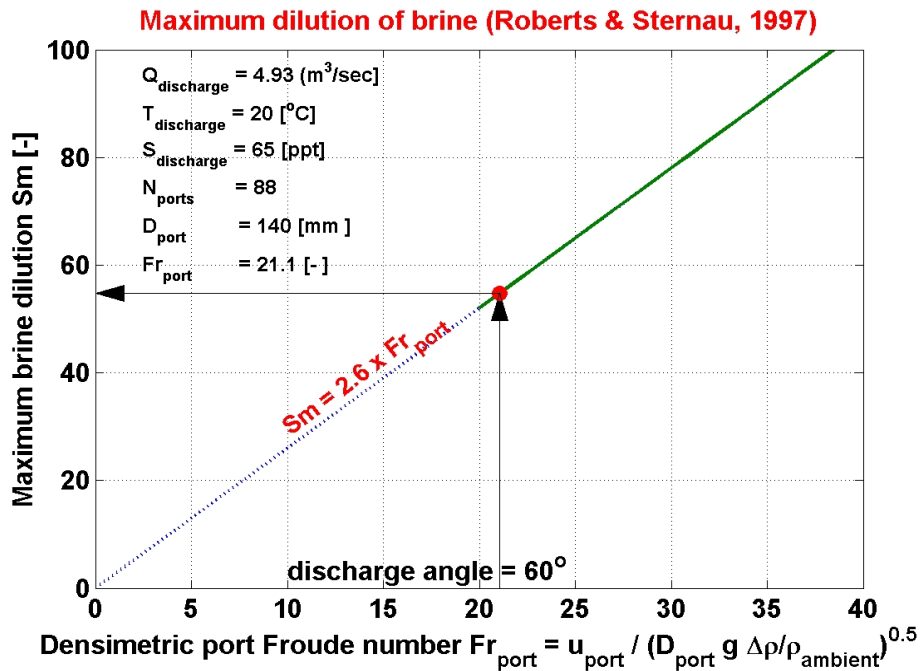


Figure 4.2 – Dilution estimate for Q_{Peak}

Fieldwork carried out by the Centre for Water Research (CWR, 2007) identified that whilst the relationship by Roberts et al. (1997) is valid for Froude numbers higher than 20, it underestimates dilutions for Froude numbers lower than 20.

Hence the use of the Roberts et al. (1997) relationship for this nominal diffuser design (i.e. all flows less than Q_{Peak}) will result in a conservative design (i.e. actual dilution will be better than design dilution).

4.4 SEAWATER SUPPLEMENTATION

For low flow conditions (i.e. where dilution at the end of the near-field fails to meet the target salinity of ≤ 1 ppt above ambient), pre-dilution with ambient seawater will take place.

Refer to Figure 4.3 over page for comparison of ‘Effective brine dilution’ versus ‘Effluent dilution’.

For all flows less than 240 MLD, it is found that an effective brine dilution of ~ 28.45 is required to meet the target salinity of ≤ 1 ppt above ambient at the end of the near-field mixing zone (refer to Appendix B for excel spreadsheet).

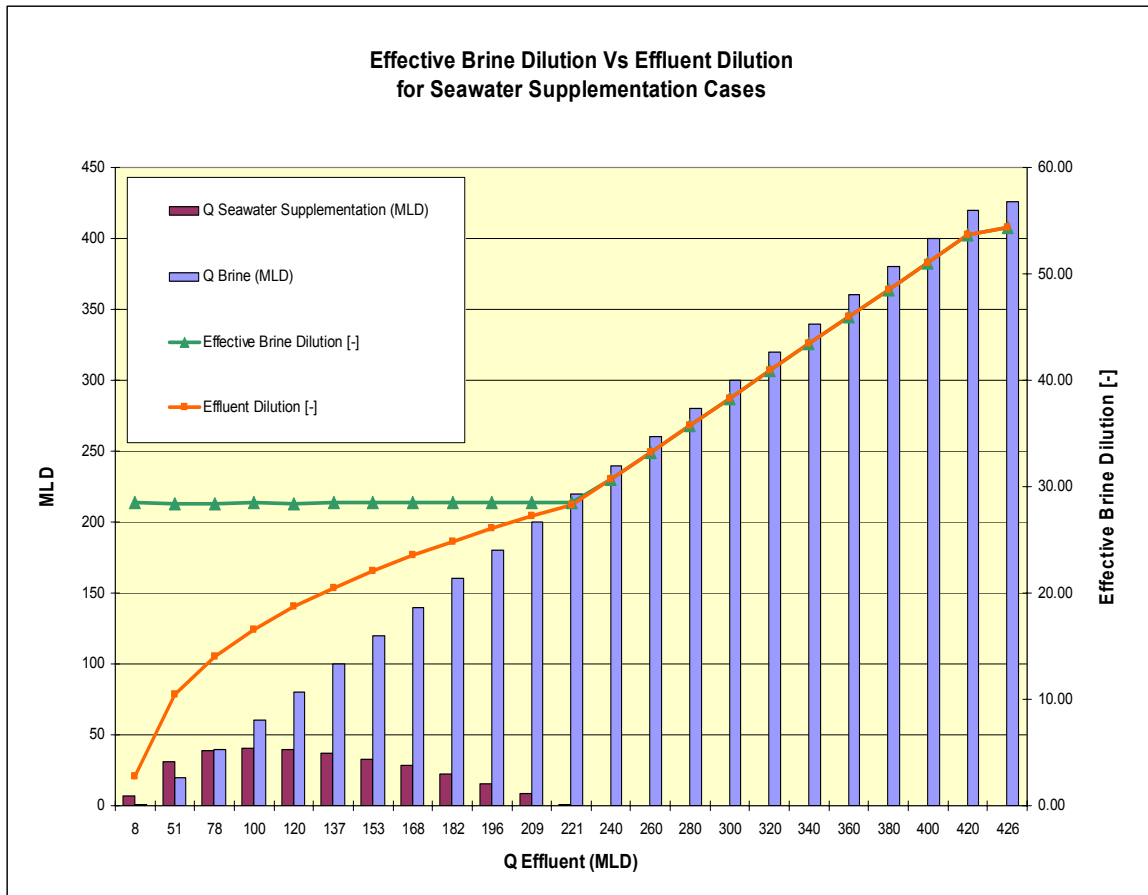


Figure 4.3- Effective Brine Dilution Vs Effluent Dilution for seawater supplementation cases

4.5 PLUME CHARACTERISTICS FROM VISUAL PLUMES ANALYSIS

Results from the *Visual Plumes* analyses for the above diffuser design suggest the following plume characteristics (prior to impacting the ocean floor) for the three flow cases.

A comparison to plume characteristics predicted by Roberts' empirical formula has been included.

4.5.1 Q_{Peak} - *Visual Plumes* analyses

Table 4.3 - Q_{Peak} plume characteristics (Visual Plumes and Roberts et al)

Plume characteristics	Visual Plumes	Roberts et al. (1997) formula
Terminal height (m)	3.4	6.4
Distance to impact (m)	7.0	7.0
Impact point dilution	28	33.2
Distance to end of near-field (m)	-	26.2
Min. spacing required between ports (m)	3	-

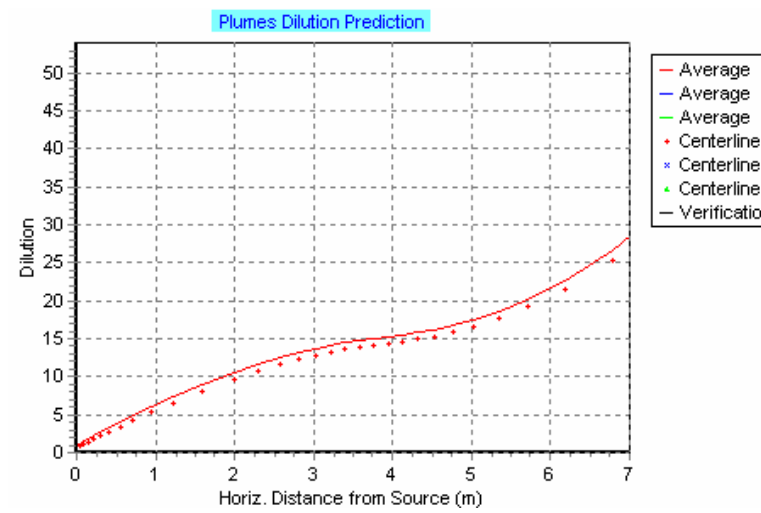
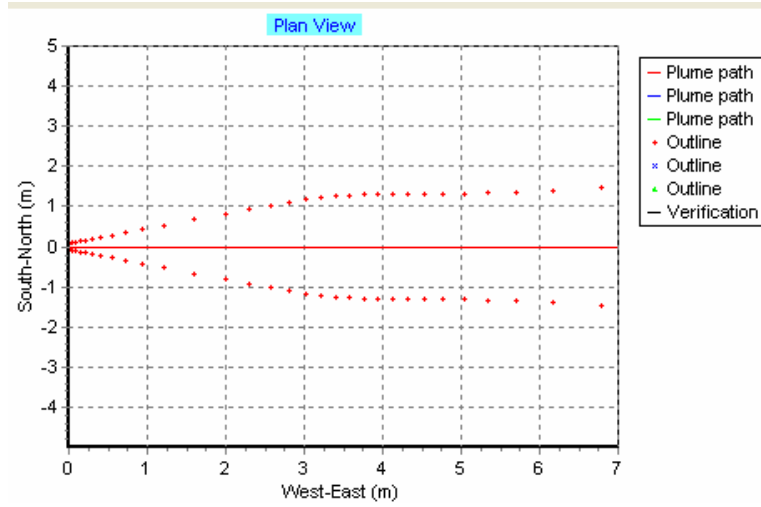
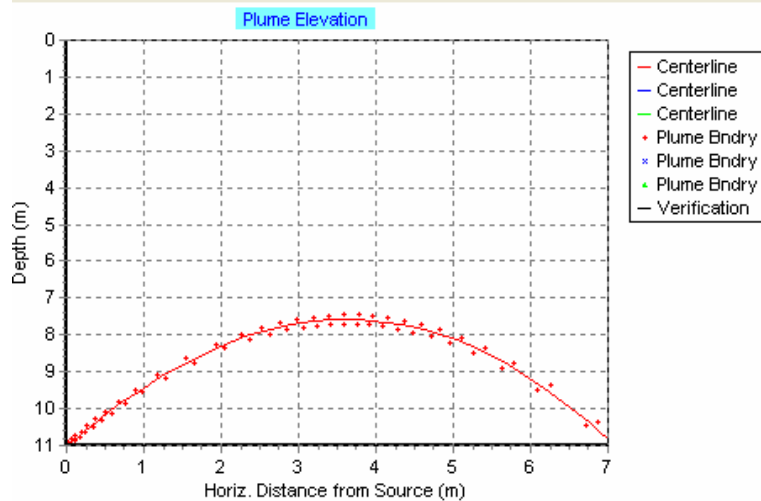
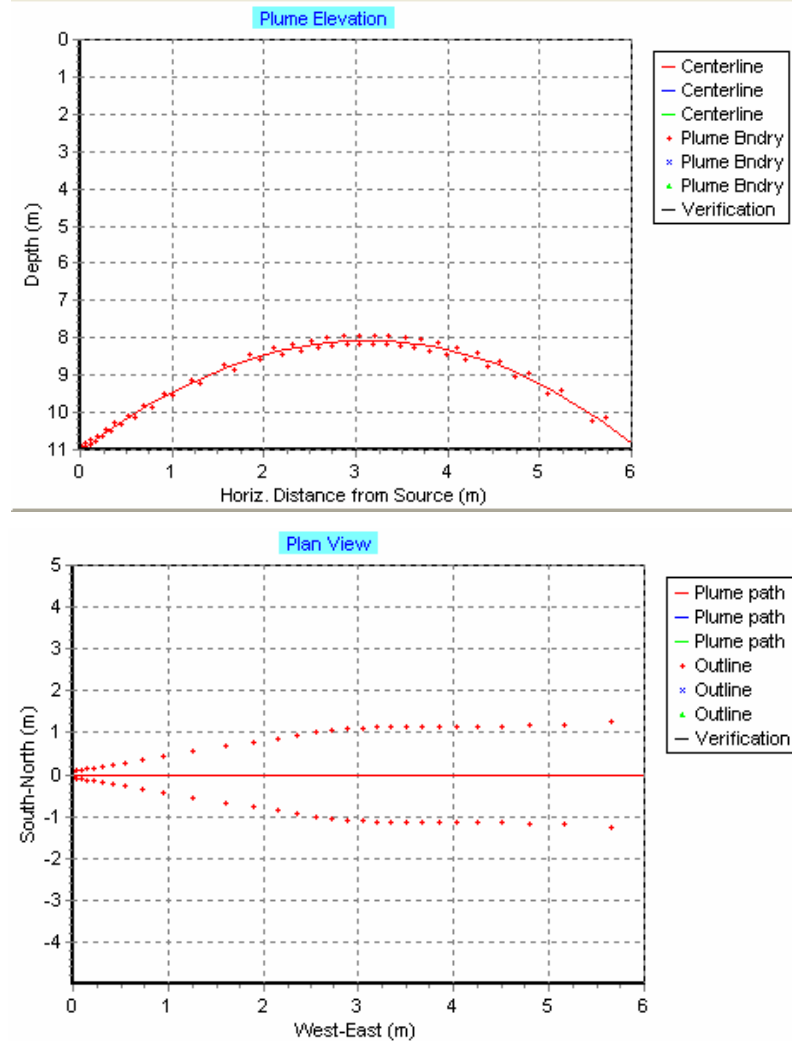


Figure 4.4 a) Q_{Peak} plume elevation b) Q_{Peak} horizontal spread (prior to impact) and c) Q_{Peak} dilution prediction (prior to impact)

4.5.2 Q_{Design} - Visual Plumes analyses

Table 4.4 - Q_{Design} - plume characteristics (Visual Plumes and Roberts et al)

Plume characteristics	Visual Plumes	Roberts et al. (1997) formula
Terminal height (m)	3.0	5.6
Distance to impact (m)	6.0	6.1
Impact point dilution	24	28.9
Distance to end of near-field (m)	-	22.8
Min. spacing required between ports (m)	2.6	-



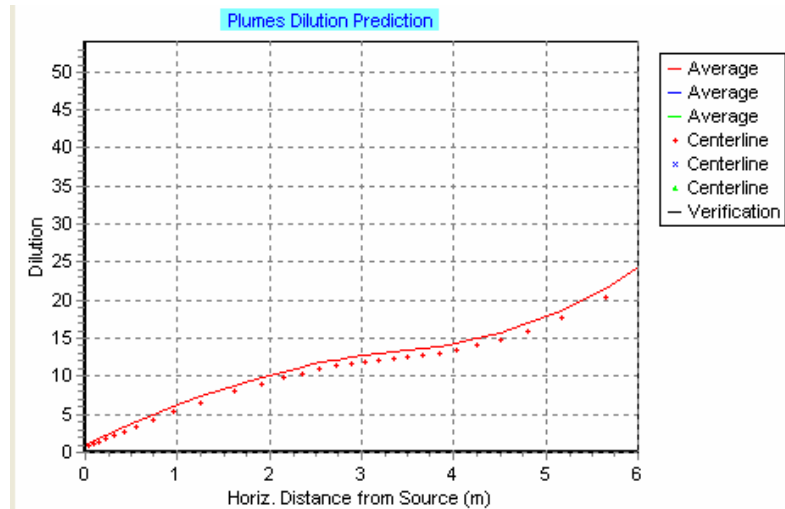
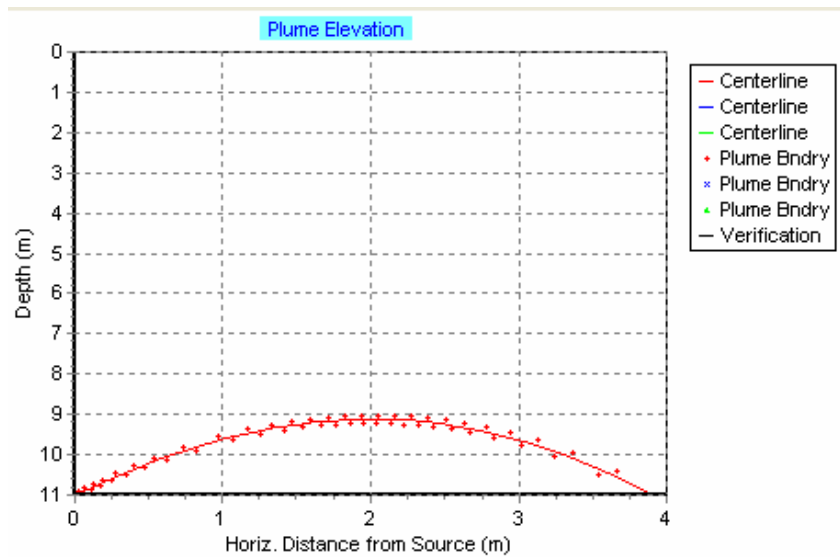


Figure 4.5 a) Q_{Design} plume elevation b) Q_{Design} horizontal spread (prior to impact) and c) Q_{Design} dilution prediction (prior to impact)

4.5.3 $\frac{2}{3} Q_{Design}$ - Visual Plumes analyses

Table 4.5 - $\frac{2}{3} Q_{Design}$ - plume characteristics (Visual Plumes and Roberts et al)

Plume characteristics	Visual Plumes	Roberts et al. (1997) formula
Terminal height (m)	2.0	3.7
Distance to impact (m)	3.8	4.0
Impact point dilution	17	19.3
Distance to end of near-field (m)	-	15.2
Min. spacing required between ports (m)	2	-



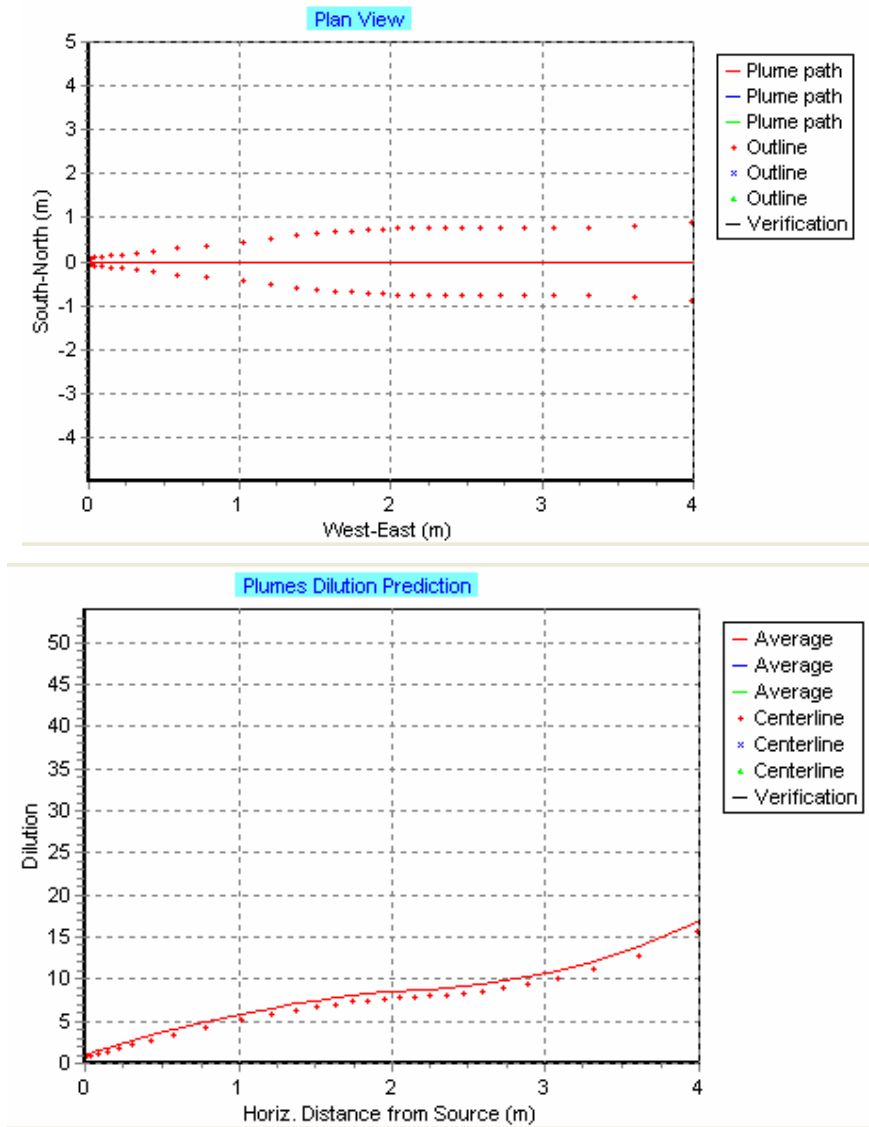


Figure 4.6 a) $\frac{2}{3} Q_{\text{Design}}$ plume elevation b) $\frac{2}{3} Q_{\text{Design}}$ horizontal spread (prior to impact) and c) $\frac{2}{3} Q_{\text{Design}}$ dilution prediction (prior to impact)

It is important to note that the *Visual Plumes* software does not recognise when the plume hits the ocean floor and therefore does not accurately model plume propagation beyond this point.

The ‘distance to impact’ values calculated by the two design methods are very consistent, whilst the ‘impact point dilution’ values are reasonably consistent.

There is considerable inconsistency in prediction values for the ‘terminal rise height’ from both methods. The prediction by Roberts et al. (1997) has been adopted for this nominal diffuser design as it has been developed based upon extensive laboratory monitoring.

The *Visual Plumes* ‘plan view figures’ give a good understanding of the required minimum spacing between ports prior to impact.

5 Conclusions and Recommendations

After thorough analysis of near-field mixing using Roberts et al. (1997) formula and cross-checking plume characteristics with *Visual Plumes*, the following diffuser design is proposed (Table 5.1).

Table 5.1 - Nominal Diffuser Design

Design Feature	Value
Diffuser port diameter (mm)	140
Spacing of ports (m)	5
Number of ports (spaced on one side)	88
Vertical angle from the horizontal (°)	60
Diffuser port depth (m)	11.0
Length of diffuser (m)	440
Length of outlet pipeline up to the diffuser (m)	600

This diffuser design will achieve the environmental criteria proposed by Water Corporation (i.e. the salinity level beyond the edge of the near-field mixing zone will not exceed 1 ppt above ambient salinity levels).

Pre-dilution of the brine discharge with seawater (at rates specified in Section 4.4/Appendix B) for low flows (i.e. less than 240 MLD) will ensure that the above environmental criteria is always met.

6 References

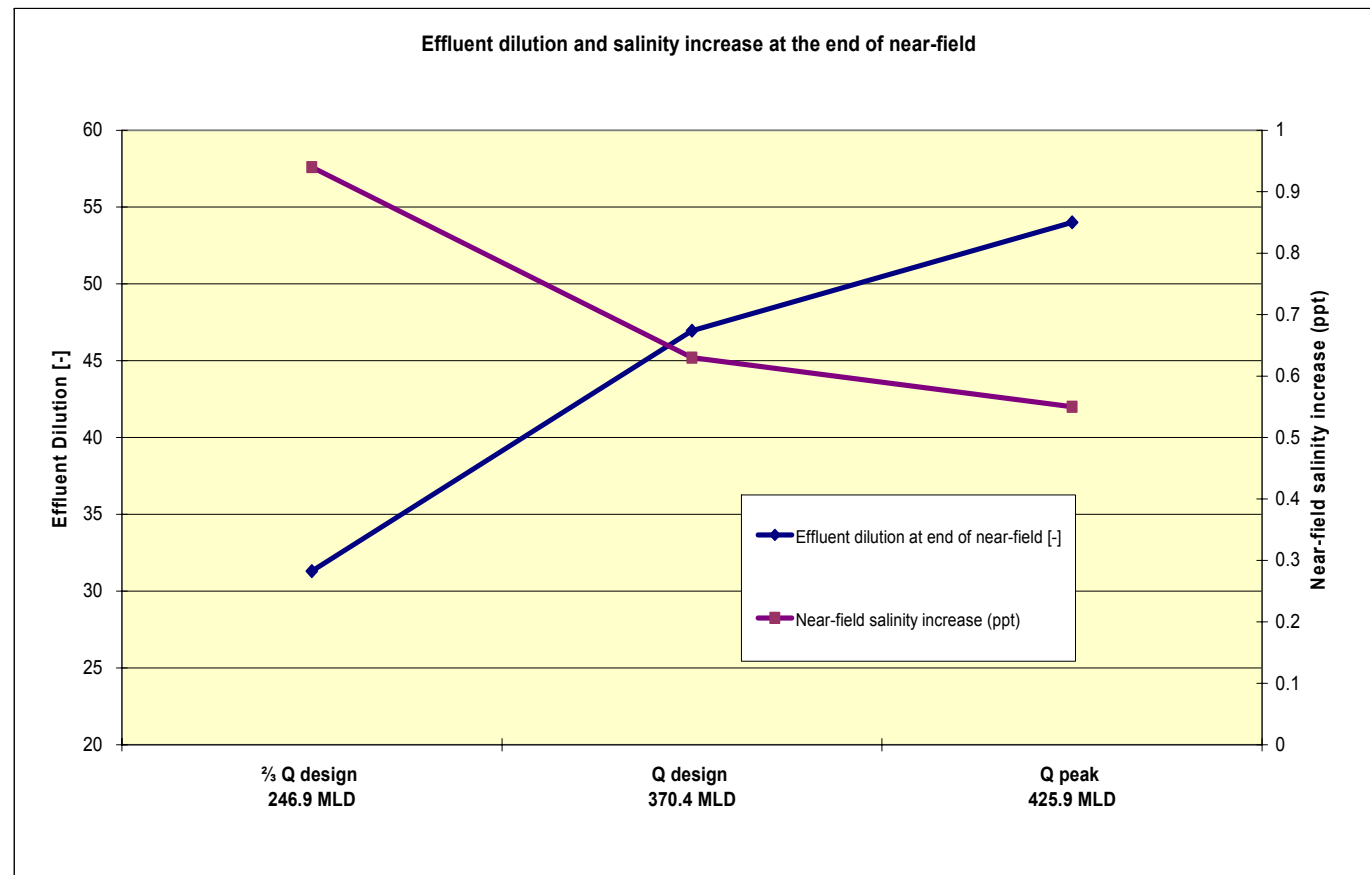
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Appendix A

**ROBERTS ET AL.
EMPIRICAL RELATIONSHIPS
EXCEL SPREADSHEET**

45% RECOVERY			Total Flow	Total Flow	Total No. of Ports	Port Diameter	Port Area	Port Velocity	Port Spacing	Salinity	Temp	Brine density	Ambient density	$\Delta\rho$	Froude No.	Terminal Rise Height	Distance to Impact	Impact Point Dilution	Distance to end of near-field	Dilution at end of near-field	Associated Concentration	Spreading Layer Thickness
303.03 ML/day	673.40 ML/day	370.37 ML/day	ML/day	m^3/s		mm	m^2	m/s	m	ppt	C	kg/m^3	kg/m^3	kg/m^3		m	m		m		ppt	m
Q design	POTABLE WATER -100GL over 330 days	PRODUCTION OF BRINE - 122.22GL over 330 days	370.37	4.29	96	140	0.02	2.90	5	65.45	20	1048.21	1025.27	22.94	16.6	5.1	5.6	26.5	20.9	43	36.68	1.6
			370.37	4.29	94	140	0.02	2.96	5	65.45	20	1048.21	1025.27	22.94	16.9	5.2	5.7	27.1	21.3	44	36.67	1.7
			370.37	4.29	92	140	0.02	3.03	5	65.45	20	1048.21	1025.27	22.94	17.3	5.3	5.8	27.6	21.8	45	36.66	1.7
			370.37	4.29	90	140	0.02	3.10	5	65.45	20	1048.21	1025.27	22.94	17.7	5.4	5.9	28.3	22.3	46	36.64	1.7
			370.37	4.29	88	140	0.02	3.17	5	65.45	20	1048.21	1025.27	22.94	18.1	5.6	6.1	28.9	22.8	47	36.63	1.8
			370.37	4.29	86	140	0.02	3.24	5	65.45	20	1048.21	1025.27	22.94	18.5	5.7	6.2	29.6	23.3	48	36.61	1.8
			370.37	4.29	84	140	0.02	3.32	5	65.45	20	1048.21	1025.27	22.94	18.9	5.8	6.4	30.3	23.8	49	36.60	1.9
			370.37	4.29	82	140	0.02	3.40	5	65.45	20	1048.21	1025.27	22.94	19.4	6.0	6.5	31.0	24.4	50	36.58	1.9
			370.37	4.29	80	140	0.02	3.48	5	65.45	20	1048.21	1025.27	22.94	19.9	6.1	6.7	31.8	25.0	52	36.57	1.9
			370.37	4.29	78	140	0.02	3.57	5	65.45	20	1048.21	1025.27	22.94	20.4	6.3	6.8	32.6	25.7	53	36.56	2.0
370.37	4.29	76	140	0.02	3.67	5	65.45	20	1048.21	1025.27	22.94	20.9	6.4	7.0	33.5	26.4	54	36.54	2.0			

MODELLING CASES	2/3 Q design	246.91	2.86	88	140	0.02	2.11	5	65.45	20	1048.21	1025.27	22.94	12.0	3.7	4.0	19.3	15.2	31	36.94	1.2
	Q design	370.37	4.29	88	140	0.02	3.17	5	65.45	20	1048.21	1025.27	22.94	18.1	5.6	6.1	28.9	22.8	47	36.63	1.8
	Q peak	425.93	4.93	88	140	0.02	3.64	5	65.45	20	1048.21	1025.27	22.94	20.8	6.4	7.0	33.2	26.2	54	36.55	2.0



Appendix B

**SEAWATER
SUPPLEMENTATION
EXCEL SPREADSHEET**

Qbrine (MLD)	Qseawater (MLD)	Qeffluent (MLD)	U (m/s)	Dreffluent (kg/m3)	g'	F	Effluent Dilution	Seffluent (ppt)	Snear_field (ppt)	ΔSnear_field (ppt)	Qnearfield_out (MLD)	Pre-Dilution	Effective Dilution of Brine
1.00	6.79	7.79	0.07	2.90	0.03	1.07	2.78	39.78	37.00	1.00	28	6.79	28.45
20.00	31.27	51.27	0.44	8.81	0.08	4.03	10.48	47.49	37.00	1.00	569	1.56	28.43
40.00	38.42	78.42	0.67	11.52	0.11	5.39	14.02	51.02	37.00	1.00	1138	0.96	28.45
60.00	40.44	100.44	0.86	13.49	0.13	6.38	16.59	53.60	37.00	1.00	1707	0.67	28.45
80.00	39.65	119.65	1.02	15.10	0.14	7.19	18.69	55.69	37.00	1.00	2275	0.50	28.44
100.00	37.05	137.05	1.17	16.48	0.16	7.88	20.49	57.49	37.00	1.00	2845	0.37	28.45
120.00	33.10	153.10	1.31	17.71	0.17	8.49	22.08	59.09	37.00	1.00	3414	0.28	28.45
140.00	28.12	168.12	1.44	18.81	0.18	9.05	23.53	60.53	37.00	1.00	3983	0.20	28.45
160.00	22.30	182.30	1.56	19.83	0.19	9.56	24.85	61.85	37.00	1.00	4552	0.14	28.45
180.00	15.79	195.79	1.67	20.77	0.20	10.03	26.08	63.08	37.00	1.00	5121	0.09	28.45
200.00	8.70	208.70	1.78	21.65	0.21	10.47	27.22	64.23	37.00	1.00	5691	0.04	28.45
220.00	1.11	221.11	1.89	22.48	0.22	10.89	28.31	65.31	37.00	1.00	6260	0.01	28.45
240.00	0.00	240.00	2.05	22.59	0.22	11.79	30.65	65.45	36.93	0.93	7356	0.00	30.65
260.00	0.00	260.00	2.22	22.59	0.22	12.77	33.20	65.45	36.86	0.86	8633	0.00	33.20
280.00	0.00	280.00	2.39	22.59	0.22	13.75	35.76	65.45	36.80	0.80	10012	0.00	35.76
300.00	0.00	300.00	2.56	22.59	0.22	14.73	38.31	65.45	36.75	0.75	11493	0.00	38.31
320.00	0.00	320.00	2.73	22.59	0.22	15.72	40.86	65.45	36.70	0.70	13077	0.00	40.86
340.00	0.00	340.00	2.90	22.59	0.22	16.70	43.42	65.45	36.66	0.66	14762	0.00	43.42
360.00	0.00	360.00	3.08	22.59	0.22	17.68	45.97	65.45	36.63	0.63	16550	0.00	45.97
380.00	0.00	380.00	3.25	22.59	0.22	18.66	48.53	65.45	36.59	0.59	18440	0.00	48.53
400.00	0.00	400.00	3.42	22.59	0.22	19.65	51.08	65.45	36.57	0.57	20432	0.00	51.08
420.00	0.00	420.00	3.59	22.59	0.22	20.63	53.63	65.45	36.54	0.54	22526	0.00	53.63
426.00	0.00	426.00	3.64	22.59	0.22	20.92	54.40	65.45	36.53	0.53	23175	0.00	54.40

