NUMERICAL MODELLING AND FIELD TRIALS FOR THE CHRISTCHURCH OCEAN OUTFALL

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Abstract
The Water Research Laboratory (WRL) of the University of New South Wales was engaged to undertake 12 months of oceanographic data collection and numerical near and far field modelling to evaluate the impacts of ocean outfall options in Christchurch Ocean Outfall in New Zealand. The data collection program comprised measurement of ocean currents, stratification and winds for twelve months and several experiments where ADCP (current) transects were gathered. The conceptual diffuser designs, near field modelling, hydrodynamic modelling and water quality modelling culminated in long term statistics of relative impact at various sensitive receiver sites

This paper presents the methods and findings as presented to the Environment Canterbury Commissioners to identify the preferred outfall site.

In 2010, WRL was commissioned to undertake field investigations on the completed and operating Christchurch Ocean Outfall. Dilution tests were undertaken to measure the rates of mixing of effluent into seawater by injecting Rhodamine WT fluorescent dye into the effluent and measuring the concentrations in the field using a fluorometer. A Seabird was towed behind or lowered from the vessel gathering pH, salinity, depth and fluorescence and was logged on a laptop onboard the vessel allowing for visualisation in real time. Dive inspections were also carried out.

This paper also discusses the field data sampling and the methods of interpretation and analysis.

Keywords
Outfall, Diffuser, Seawater, Dilution, Plume, Mixing, Near Field, Dye Tracer

INTRODUCTION

Christchurch in New Zealand has wastewater treatment and disposal facilities which include secondary treatment at the Bromley wastewater treatment plant. This plant previously discharged via a series of final treatment ponds into the Avon Heathcote estuary. Christchurch City Council (CCC) commissioned URS NZ to investigate future options for the treatment and disposal of the city's wastewater. The Water Research Laboratory (WRL) of the University of New South Wales was engaged in 1999/2000 to undertake oceanographic data collection and numerical near and far field modelling to evaluate the impacts of three short listed options: an estuary discharge and two ocean outfall options 2 km and 3 km offshore of South Brighton. Following these and other extensive studies completed on behalf of CCC, an estuary discharge with upgraded treatment plant facilities was selected by the Council as their preferred option.

In 2002, the Environment Canterbury Commissioners granted CCC consent for continued discharge of treated wastewater to the Avon Heathcoe estuary for a period of 5 years only. Further investigations were subsequently initiated by CCC, with the aim of commissioning an ocean outfall within the 5 year time frame.

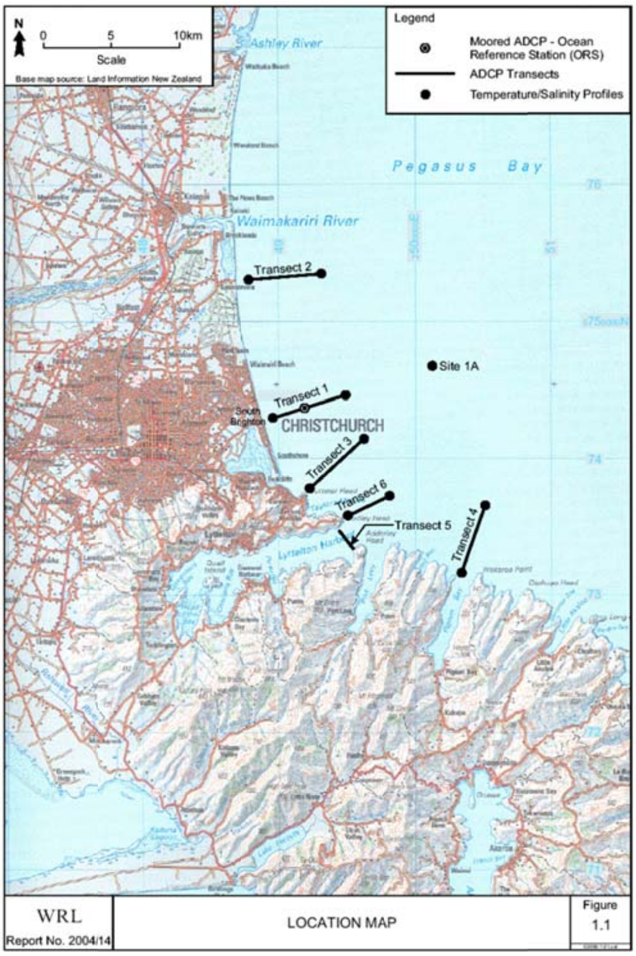
WRL was commissioned by CCC and URS NZ in 2002 to undertake a further 12 months of oceanographic data collection and water quality modelling of the 2 km and 3 km ocean outfall options. The data collection program comprised measurement of ocean currents, stratification and winds for twelve months and several experiments where ADCP (current) transects were gathered. The conceptual diffuser designs, near field modelling, hydrodynamic modelling and water quality modelling culminated in long term statistics of relative impact at various sensitive receiver sites.

In 2010, WRL was commissioned to undertake field investigations on the completed and operating Christchurch Ocean Outfall. Dilution tests were undertaken to measure the rates of mixing of effluent into seawater by injecting Rhodamine WT fluorescent dye into the effluent and measuring the concentrations in the field using a fluorometer. A Seabird was towed behind or lowered from the vessel gathering pH, salinity, depth and fluorescence and was logged on a laptop onboard the vessel allowing for visualisation in real time. Dive inspections were also carried out.

The measurements demonstrated that the outfall is operating as designed and achieving excellent dilutions with the ocean. These measurements provide one of the most extensive datasets on an actual outfall near field behaviour. Conditions on two days of sampling were extremely calm with very little current which allowed for more than five hours of repeat transects to be taken along the edge of the mixing zone. The median of samples show a very good match with near field predictions but the data set presents a large variance in individual samples. This paper also discusses the field data sampling and the methods of interpretation and analysis.

DATA COLLECTION

Figure 1 - The region offshore of Christchurch and Key Data Collection.



Between 25th January 2003 and 29th February 2004 current measurements were obtained from a moored ADCP (Acoustic Doppler Current Profiler) near the proposed ocean outfall site. For the moored location, the ADCP was deployed in a frame on the seabed 2.5 km offshore of South Brighton in 14 m water depth. This ORS data was later crucial for providing boundary conditions to the numerical model of the ocean currents. The ADCP was programmed to continuously record an average current speed and direction profile every 10 minutes with data spaced vertically in 1 m bins from 2.5 m above the seabed to near the surface.

Current profiles were undertaken from a vessel mounted ADCP to record data in 1 metre depth bins at 10 second intervals. These were undertaken at various locations on two different occasions as shown in Figure 1. The first one-day current profiling exercise was undertaken on 26 January 2003. The second two-day current profiling exercise was undertaken on 29-30 August 2003.

Tide gauges are maintained at Lyttelton Harbour (Lyttelton Port Company) and Sumner Head (NIWA/ECAN). Later modelling used the predicted tide level at Sumner Head, obtained from analysis of 12 months of measured tide levels from the site (for the year 1998) using the method of Foreman (1978).

An automatic weather station was operated by NIWA at Christchurch Airport, approximately 17 km inland and to the WNW of South Brighton. Hourly wind speed and direction data was recorded at the station in 10 degree directional bins. From this data it is evident that the predominate wind direction and the majority of strong wind patterns are from the ENE.

A thermistor string recorded stratification from 25 January to 8 May 2003. During each of the ADCP exercises a Seabird SBE Sealogger was used to record vertical CTD (conductivity, temperature, depth) profiles from which salinity and water density were obtained. Available thermistor and density data showed very little temperature or salinity stratification at the sites profiled. A slight increase in stratification was found in proximity of the Waimakariri River due to freshwater discharges. Nonetheless, across the proposed outfall locations density and salinity measurements did not indicate stratification with density ranging from 1024.2 to 1026.2 kg/m^3. Based on these datasets, the effects of density stratification due to temperature on the currents were expected to be negligible and were not therefore included in the hydrodynamic modelling.

Spectral analysis of the available current data shows that tides and weather patterns influence currents in Pegasus Bay. Longshore and shore normal current spectra from the ORS depict a distinct peak at the M2 tidal frequency of approximately 12.4 hours. Significant spectral energy is also apparent in the 3-10 day weather patterns. This illustrates that while the tidal regime plays a major role in controlling currents, additional climatic variability such as winds will have a significant impact and need to be considered in numerical simulations. As such, tidal boundary conditions alone would be inadequate for hydrodynamic modelling.

The impact of winds, and its spatial variability across the study domain, on the current direction is most apparent in the top profile of the water column. As this is the location in the water column where the buoyant discharged plume will rise to, the wind energy is an important consideration in numerical simulations.

Currents across Pegasus Bay vary slightly due to the influence of wind and the direction of the shoreline. Current direction between data collected at Waimakariri (on a separate investigation) and Christchurch varies with both the direction of the shoreline and the wind energy. Nonetheless, correlations between the two datasets show that regardless of depth, the direction of currents at any time period is similar for both sites. The correlation between the Waimakariri site and the Christchurch site also indicate that in the majority of time the current regime throughout Pegasus Bay is a uniform flow northward or southward without any large scale eddying or circulation.

NEAR FIELD MODELLING

JETLAG is a near field model designed for the prediction of three dimensional trajectories of buoyant jets in a stratified ambient current (Lee and Cheung, 1990). The model treats the unknown jet trajectory as a series of ‘plume elements’ which rise due to buoyancy while gaining mass through entrainment of the ambient fluid. This model was selected as the performance of JETLAG had been used and verified in Hong Kong waters for multi-port outfalls in similar depths to the Christchurch outfall (Horton et al, 1996).

Input to JETLAG consists of parameters describing the outfall characteristics (depth, number of ports, port diameter, spacing and discharge angle), the effluent characteristics (total discharge rate, temperature and salinity) and the receiving waters (current, temperature and salinity throughout the water column). The model calculates the average effluent dilution, plume trap depth and plume radius as it rises through the water column.

The outfall diffuser design consisted of a line of 13 rosette diffusers spaced at 20 m intervals over a distance of 240 m. Each diffuser consists of eight ports, fitted with a rubber duckbill valve designed to allow flow in one direction only and prevent seawater intrusion into the outfall. At the ADWF (average dry weather flow) discharge, the effective diameter of the duckbill valves on the diffuser ports was assumed to be 0.125 m. The eight jets on each riser were modelled together, as a horizontal discharge into a cross flowing current. This method predicts an average dilution for each riser. Based on the JETLAG modelling the jets from adjacent ports were not expected to merge.

Using the twelve months of current data from near the outfall sites, a twelve month JETLAG simulation was undertaken for the various outfall options discharging the design ADWF of 2.31 m^3/s. Based on the offshore CTD profile data, the salinity of the receiving waters was assumed to be vertically uniform at 33.8 ppt. The near field dilution changes with time as the speed of the ocean currents change with time. The minimum near field dilution will be achieved into stationary receiving water (e.g. at slack tide or turning water).

Table 1 presents the statistical likelihood of near field dilutions from the 3 km Ocean Outfall (which was finally determined as the preferred option). The minimum dilution achieved was 61.

Table 1 – Predicted Near Field Dilutions

Percentile (% of time)	**Dilution**
95% of the time the dilution rate will be less than:	896
50% of the time the dilution rate will be less than:	240
10% of the time the dilution rate will be less than:	102
5% of the time the dilution rate will be less than:	96
Min dilution rate (during a stationary tide):	61

Near field modelling also indicated the extent of the initial mixing zone which for 90% of conditions would be within 22m of the diffuser line.

FAR FIELD MODELLING

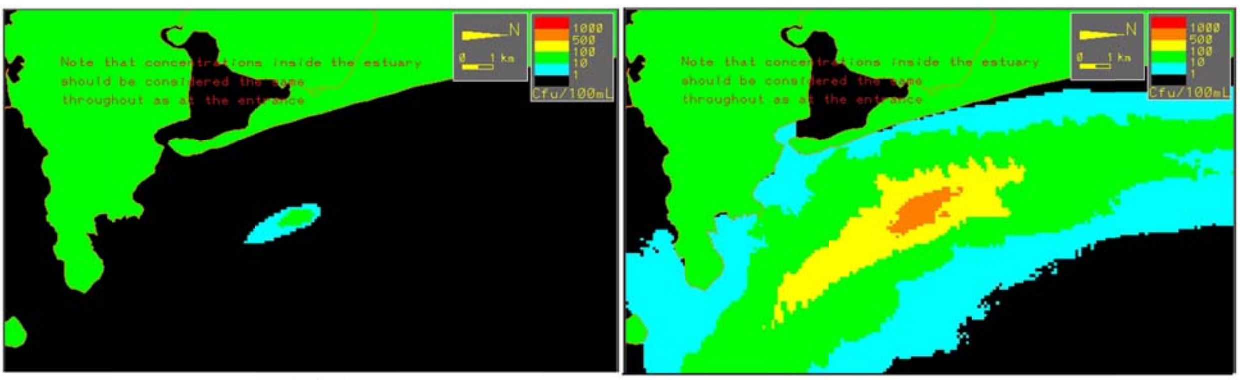
The hydrodynamic model of the currents in western Pegasus Bay was established using the three-dimensional finite element model RMA-10. The hydrodynamic model aims to reproduce the observed current patterns due to tides, local winds and larger scale ocean currents within the study area. RMA-10 is a three-dimensional finite element hydrodynamic model for stratified flow (King, 1993). The shallow water wave form of the Navier-Stokes equations (the complete equations governing fluid motion) are solved in three dimensions to obtain velocities and water surface elevations at each node on the finite element mesh.

Bathymetry data and other geographic information used for setting up the model were obtained from a number of sources. A partial slip boundary (currents can move against the shoreline with some friction) was used along the shoreline, with friction throughout the model specified using a Manning's n. The model was run using a half hourly time step. Boundary elevations were calculated from the measured current and wind data, using the elevation gradient boundary condition method described in Cathers and Peirson (1991). Wind was applied as a surface stress.

The far field behaviour of the effluent plumes from the ocean outfall options were modelled using the particle tracking model 3DRWALK (developed in-house at WRL). In 3DRWALK, the outfall discharge is represented by a large number of particles in the model, each of which is carried by an input current field, with diffusion included as a random walk step during each time step.

Both the hydrodynamic model RMA-10 and the particle tracking model 3DRWALK were run for the 12 month period of collected data. Plumes were added to the far field model over the depth of the water column as predicted by JETLAG. The output from the far field water quality model was statistics of impact at certain locations, animations of plume behaviour over the period and contours of statistical impact.

Figure 2 – Contours of Faecal Coliform Concentrations Exceeded at the 50th and 99.9th Percentiles.



MEDIAN

99.9%ILE

Simulations were undertaken with constituents of faecal coliforms, a 'conservative' pollutant and a somatic coliphage virus. Tables of impact were generated of the impact at various locations from each of the considered outfall sites. This allowed for quantitative comparison of outfall options.

The results and comparison of site performance is beyond the scope of this paper. Full results are available in Miller *et al* (2004). By way of example contours of the concentration of faecal coliforms exceeded 50% of the time and 0.1% of the time are presented in Figure 2. Note that the concentrations on these plots have been based on an initial concentration of 10000 units/100mL.

OBJECTIVES OF THE DILUTION TRIALS

The conditions of consent to build the outfall required dilution trials be undertaken. The fundamental basis of the dilution trials was the injection of a tracer into the effluent at a known concentration followed by the measurement of tracer concentrations in the ocean. The ratio of the concentration in the effluent to the measured concentration in the ocean is the achieved dilution. The tracer is a substance not otherwise found in the ocean.

The primary objective of the dilution tests was to ensure that the minimum dilutions are being achieved. As presented earlier in this paper, the Christchurch Ocean Outfall diffuser was designed to achieve a minimum dilution of 61 times.

Conditions were very calm with negligible currents on both days of the dilution tests. These quiescent conditions allowed us to directly measure the performance of the diffuser near the worst case conditions for dilution. Currents were negligible (below 0.02 m/s) and winds were very mild. The outfall plume could be discerned as slowly moving northwards, although oranges (used as drogues) thrown into the water moved less than 400 m during the three hours on site each day. The water column had no measurable stratification with salinity of 33.2 ppt and temperature of 14 ^{o}C.

The sampling program was designed on the fundamentals of near-field mixing. The jet and plume behaviour of the near-field results in constantly changing temporal and spatial conditions. It is very difficult (if not impossible) to take samples at the actual end of the near-field as this is changing and moving. Instead, measurements were taken in the areas immediately about and within the near-field over an extended period to obtain a large number of samples to provide statistical measure of the near-field dilutions and size of the near-field.

Beyond the near-field, additional dilutions are achieved through mixing by currents and winds as the plume is advected away. However, under quiescent conditions, this far-field mixing is negligible and the plume front spreads only by displacement with the continual effluent discharge and entrainment of seawater.

METHODS FOR THE DILUTION TRIALS

Discharge of effluent was from large ponds with adequate storage to ensure that the flows could be maintained at the design flow rate of 2.3 m^3/s by adjusting the control valve and in some instances about high tide, turning the pumps on. Flows were measured by an electromagnetic flow meter which could be read directly on a SCADA system terminal. The control valve was adjusted using the same terminal.

Rhodamine WT was injected into the effluent stream through a tapping point on the gravity fed pipeline within the pump station. The location of the tapping was well suited for the rapid mixing of the Rhodamine WT and effluent within the pipeline. The rate of injection was determined as 8.1

litres per hour. The Rhodamine WT used was 20 % active which resulted in an effluent concentration of Rhodamine WT of 195 parts per billion (ppb). This rate was based on a three hour field experiment, the expected near-field mixing and the suitable range for detection in the field (being 0.03 to 100 ppb). The injection of Rhodamine WT dye commenced approximately 1.5 hours before it was observed in the ocean.

Field measurements of the Rhodamine WT concentrations were made using a Chelsea Mini-tracker fluorometer attached to an SBE 19plus SEACAT Profiler (Seabird). The Seabird was towed behind or lowered from the vessel using the available winch arm. The data from the Seabird included pH, salinity, depth and fluorescence and was logged on a laptop onboard the vessel allowing for visualisation in real time.

Positioning of the vessel was determined by GPS using a Garmin GPSMAP 76CSx receiver. The positioning was accurate to better than 10 m. Currents were measured using a 600 KHz RDI Workhorse Sentinel Acoustic Doppler Current Profiler.

RESULTS OF THE DILUTION TRIALS

Profiles of the water column showed that the plume was within the top twelve metres of the water column with reasonably constant dilutions over the top ten metres. There was no measurable plume in the lower part of the water column.

There were many transect lines undertaken throughout the experiment, however only those directly along the diffuser alignment are presented in this paper. The “Diffuser Line” provides the best representation of the end of the near-field mixing. The diffuser line was repeated transected throughout both days of the experiment.

During all transects the depth of the Seabird was one of the parameters recorded. Enough cable was released so that the depth of the Seabird could be maintained in the depth range of one to four metres by varying the speed of the vessel. The depth and the fluorescence could be seen in real time allowing instructions of speed and transects to be communicated directly with the skipper. Transects were generally taken with a vessel speed between 2 and 4 knots.

Depths of measurements were generally within the 1 to 3 m range but varied up to 5 m depth. Based on the vertical profiles showing uniform dilutions in the upper part of the water column, all transect data was analysed without considering depth. Also, environmental conditions did not vary throughout each day, so all transect data was analysed without considering time. Finally the coordinates of each measurement were perpendicularly projected onto analysis lines so that the spatial measurement could be analysed as chainage. In summary, the five dimensional data set (east, north, depth, time and fluorescence) was reduced to a two dimensional data set (chainage and fluorescence) along each analysis line. All transects that were within 50 m of the line of diffusers were included.

Figure 3 presents all data collected along the diffuser line during Day 1 (19^{th} April 2010) and Figure 4 presents all data collected along the diffuser line during Day 2 (21^{st} April 2010). Each figure presents the fluorescence measurement converted to a dilution and spatial statistics of the samples. A 20 m moving filter has been applied to the data sets in order to calculate the median, 10th percentile, 90th percentile and geometric mean. Note that all samples have been included in the statistical analysis, however, for presentation purposes the graphs show a maximum dilution of 200 times.

Figure 3 – Dilutions Measured Along the Diffuser Line on Day 1

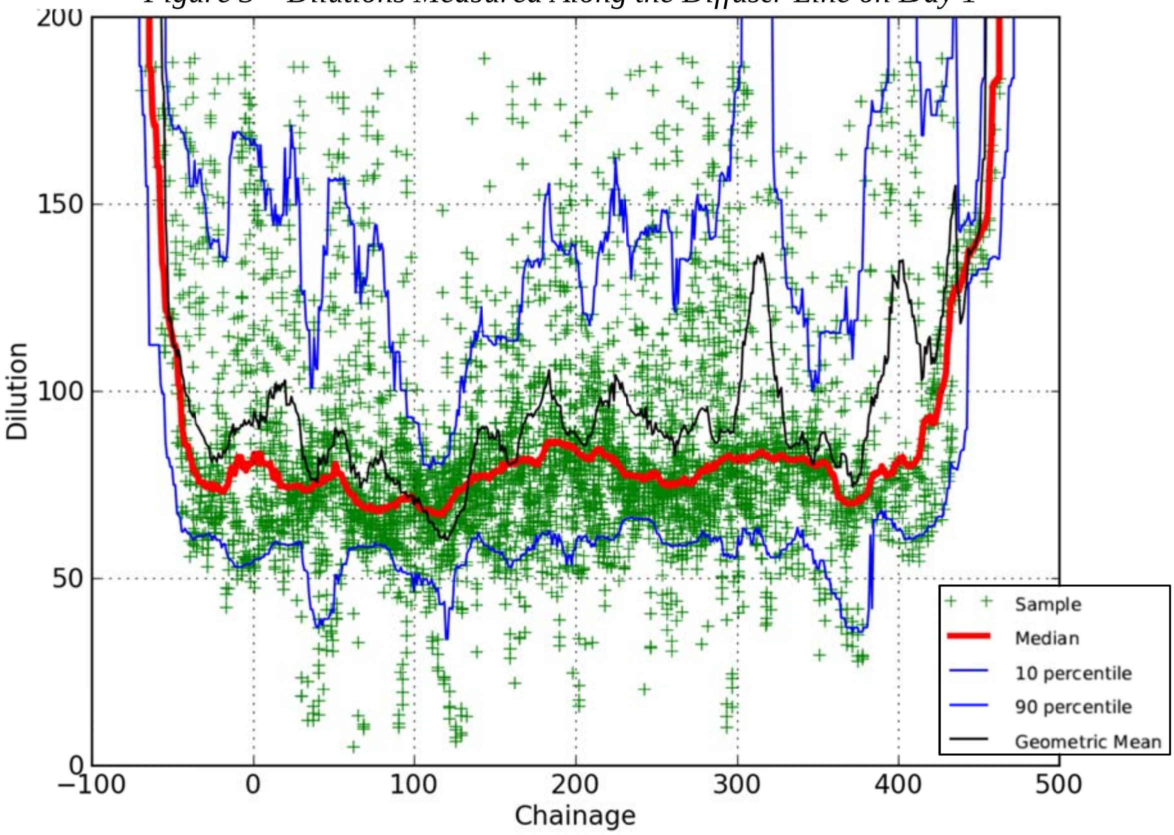
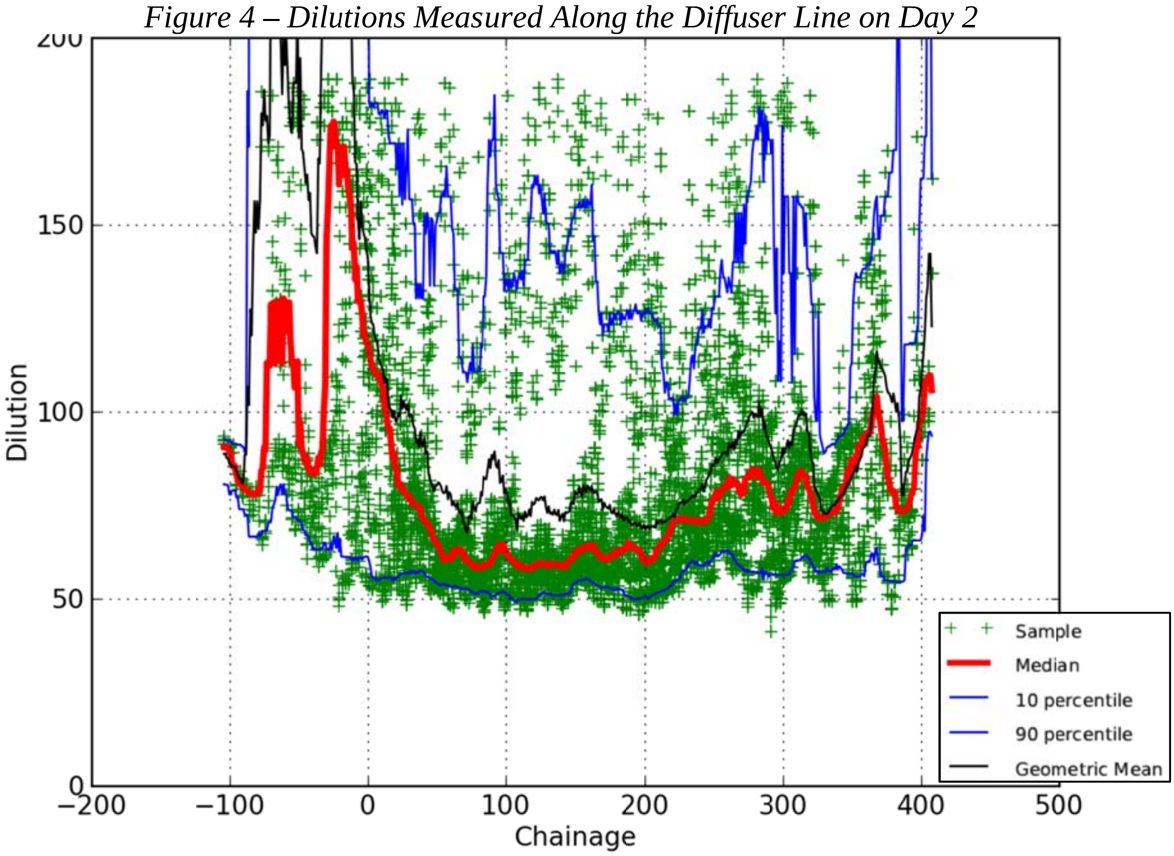


Figure 4 – Dilutions Measured Along the Diffuser Line on Day 2



As expected for a real plume measured several times, there is a considerable range of observations. Some of the variation will be due to actual spatial variations on each individual transect and some of the variation will be due to the above-mentioned assumption to not analyse time and depths separately. However, this measure of variability should be considered by anyone taking random samples from within a plume and inferring the overall dilution of the plume.

The predicted performance of the diffuser was to achieve a minimum dilution of 61 times as presented by Christchurch City Council in the resource consent hearings. This dilution represents the expected performance after reasonable mixing within the near-field. Mixing in buoyant plumes can be described as having a bell shaped Gaussian distribution, the centre of which is as predicted by near-field models. When discussing the performance of a diffuser it is important to compare the test data to the comparative design performance data, which is the mid point of that distribution. As such, the median was considered to be the most appropriate representation of the average dilution along the transect, while the 10th and 90th percentiles provide the confidence interval. The mean was not used directly as it provided higher dilutions weighted too heavily by extremely large dilution samples.

In summary, the dilution trials validated the near field predictions made during the design phase of the project. Full analysis is presented in Miller *et al* (2010).

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