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WASTEWATER DISCHARGE AT CASEY STATION, ANTARCTICA

by

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Abstract

Over the summer period of December 1997 / January 1998, a programme of field work was undertaken as part of a research project to develop numerical models of the wastewater discharge systems entering the marine waters off Casey Station in Antarctica. Samples were evaluated for ammonia, total phosphorus, and four categories of bacteria of the study period, and levels compared with the wastewater treatment plant influent and effluent, and marine background levels. Elevated levels of all parameters measured were found in the vicinity of the discharge, an area frequented by penguins from the nearby rookery. Dilution factors were calculated for each of the three parameters and range from 4 for phosphorus to 600 for bacteria. The study also found that levels of the three measured parameters increased as the air temperature increased due to accelerated melting of the snow and ice through which the wastewater flows before entering the marine environment.

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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1. INTRODUCTION

The continued concentrated presence of humans at station sites around Antarctica has led to the release of contaminants into an otherwise pristine environment. On a continental scale, the level of contamination is relatively minor; however because the majority of life in Antarctica, including humans, is concentrated into limited ice-free areas, the effects of contamination can be substantial. The impacts tend to be exacerbated due to cold temperatures, shallow or non-existent soil profiles and the restricted mixing of the marine environment adjacent to stations. Increased concerns that human activities are impacting the earth on a global scale have motivated countries operating in Antarctica to adopt more stringent operating procedures, significantly reducing the release of contaminants and reducing the overall impact on the fragile environment. The Australian Government has developed goals to protect the Antarctic environment, which include taking action to fulfil international obligations aimed at reducing or eliminating human impact.

Probably the most common contaminant resulting from the relatively short human involvement in the Antarctica is human waste. This waste has been commonly discharged into the marine environment with little or no treatment. In the early days of exploration and whaling, this discharge probably had minimal impact, but today, when station populations can exceed 1,000 persons, the impact may be significant. Though the Australian station populations are below 100 people, the discharging of wastewater directly into the ocean may have a deleterious effect on the fragile marine life. The extent and magnitude of the impact arising from the near shore discharge of wastewater has not been adequately quantified at most (if any) stations in the Antarctic.

A study was begun at Casey Station, Antarctica in December 1997 investigating the impact of wastewater disposal into Shannon Bay after treatment by a rotating biological contactor (RBC) system. Four water quality parameters were monitored in Shannon Bay from mid-December, 1997 to early January 1998; ammonia, phosphorus, biological oxygen demand (BOD) and bacteria counts. It was anticipated that the data collected would aid in determining the level, type, and extent of impact, as well as in developing a numerical model of the contaminant migration within the Bay. The results of this study are presented in the following pages of this report.

2. BACKGROUND

Literature on the fate of wastewater discharged into the Antarctic marine environment appears to be limited to:

(i) several small but related studies at McMurdo Station;

(ii) one study on human derived contaminants at Davis Station; and,

(iii) some general research on waste degradation in the Antarctic waters.

Howington et al., (1992a; 1992b) defined the spatial distribution and movement of the sewage outfall plume at McMurdo Station on two occasions in the austral spring of 1992 using coliform densities as a tracer. The study concluded that the sewage plume covered the 1 km of shoreline adjacent to the Station and extended 200-300 m seaward. Venkatesan and Mirsadeghi (1992) also investigated the extent of sewage contamination at McMurdo by analysing sediment cores and surface grab samples for coprostanol and epicoprostanol. They found similar results on the distribution of sewage but also found trace amounts of coprostanol in other areas that they tentatively attributed to seals.

Howington et al. (1994) investigated the effects of temperature on BOD and found that it was reduced significantly in the McMurdo marine environment. This implies that the carbon in the wastewater is not utilised by bacteria and therefore is being deposited as organic carbon rather than being converted to CO_2.

Railsback (1992) simulated the near-field mixing of the wastewater discharge in McMurdo using CORMIX1. His results indicated that surface discharge would lead to much less mixing and settling of solids over a greater area when compared to a submerged system. Railsback (1992) ran a number of simulations of the system using different combinations of current speeds, effluent characteristics and outfall design. However, the results were not compared to field data so it is not known if the model accurately represents the marine system.

Crockett (1997) provides water quality data collected in the vicinity of the sewage outfall area at McMurdo during November 1994. A variety of parameters were measured, including ammonia, phosphorus, and BOD, from the three sets of samples tested. From the limited sampling set, Crockett (1997) found that there was no evidence of elevated levels of nutrients in the water surrounding the outfall and only a small trend in the BOD data that was minor. It should be noted that the only treatment of wastewater that occurs in McMurdo is maceration and mixing with reject water from the station's reverse osmosis plant, and that the wastewater is released from a pipe that is located 1.5 m above the ocean floor at a depth of 17.5 m. The pipe end is approximately 70 m from shore.

Lenihan et al. (1990), Kennicutt et al. (1995), Risebrough et al. (1990), and Lenihan (1992) have looked at other forms of anthropogenic pollution in Winter Quarters Bay adjacent to McMurdo. They have published brief reports on their scoping work. However, no substantial work locating the sources, the rate of degradation or areal extent has been found in the literature.

Green and Nichols (1995) conducted a study of hydrocarbon and coprostanol levels in the seawater, sea-ice algae and sediments near Davis Station as part of a region survey and fuel spill experiment. They found significant faecal contamination both on the shoreline and in the marine sediments around the outfall. Levels ranged from 13.2 μg/g in the sediments to 5.0 μg/g onshore. PD Nichols and colleagues have also conducted numerous studies on coprostanol and other sterols in the Antarctic waters, work that contributes to the general knowledge of waste degradation in the marine environment. No other significant work on the human impacts on the Antarctic marine environment from wastewater has been found in the open literature.

3. CASEY STATION

Casey Station is located at 66° 17'S, 110° 32'E on Bailey Peninsula, just outside the Antarctic Circle, and is one of three permanent Australian stations on the continent. The population varies from around twenty in the winter months to over seventy for short periods during the summer. Melt water collected in a pond behind the station is the main source of potable water. This supply is sometimes augmented from a pond further from the station when required. Water is pumped from the pond into heated storage tanks where it is held prior to distribution to buildings around the station. About 1.5 million litres of water are used annually, with the bulk of this passing into the wastewater system.

The wastewater system consists of a collection network, a treatment facility and a discharge pipe. The major component of the system is the treatment facility that consists of a rotating biological contactor unit that contains six treatment stages, a primary sedimentation tank and a clarifier. The system was designed to treat a peak hourly flow of 1,770 L (0.5 L/s) and a maximum daily flow of 6,000 L (0.07 L/s). The output from the facility is piped downhill from the plant towards Shannon Bay where it is released onto snow and rocks above and south of the water (see Figure 1). The released wastewater follows an unknown path for tens of metres before entering the water. The snow and ice cliff at the edge of Shannon Bay below the end of the discharge pipe shows an area of marked discolouration, indicating that the wastewater flows through that area during at least part of the year. It is surmised that at least a portion of it is frozen before reaching Shannon Bay during the winter months in the area of discolouration.

The wastewater treatment plant does not produce a constant discharge due to the inclusion of a retention tank, and thus flow into Shannon Bay is not constant. A float switch in the tank starts a pump when the liquid level reaches a set height, resulting in the discharge of the bulk of the wastewater being held. During the busy summer months, the tank empties about once per hour during times of peak water usage. During the winter months it may only empty, at most, several times per day. During peak water usage times in the summer months, the clarifier is overloaded and a larger than design sediment load passes into the retention tank and out through the discharge pipe to the ocean. The batch nature of the discharge from the treatment plant further complicates the flow regime of the wastewater into Shannon Bay, providing an approximately 3-4 minute slug on an irregular basis.

4. SHANNON BAY

Shannon Bay is aligned approximately east/west and is about 200 m long and 100 m wide. The water depths on the western end of the bay are approximately 20 m, while the eastern end is closed by the isthmus that connects Budnick Hill to Bailey Peninsula. The bay is covered by ice throughout much of the year and is sheltered to some extent from the strong easterly winds by Budnick Hill. Therefore, the major regional driving mechanisms are reduced compared to Newcomb Bay and the surrounding waters. The currents and tides in Shannon Bay were monitored as part of this project and the overall Human Impacts Program at Casey Station. The results of this monitoring are reported in Cathers et al. (1998). In summary, it was found that during periods of light winds, currents at depths of 18 m were below 5 cm/s, which is at or near the sensitivity threshold of the S4 current meters that were deployed. During periods of high winds, the current speeds increased and were in the general direction of the prevailing wind, approaching 20 cm/s on one day. However, these high current speeds were rare and over the bulk of the monitoring period the speeds were below the 5 cm/s level.

5. EXPERIMENTAL METHODOLOGIES

To reasonably analyse the dispersion of pollutants in Shannon Bay, two major factors needed to be investigated. These were the movement of water into and out of the Bay due to currents and winds, and the spatial distribution of wastewater (water quality parameters) within the Bay. Since the focus of this report is on the water quality testing, only a brief description of measurement of currents will be provided. A more complete description is provided in Cathers et al. (1998).

The movement of water into and out of Shannon Bay by tides, currents, and wind-induced currents were measured using two methodologies. The first was using two S4 current meters that were moored at the opening of the Bay at a depth of about 13 m (water depth of 18 m). These instruments collected data at ten minute intervals and provided a continuous record of water flow at depth. Also of interest in the study were the surface currents present in the Bay. Since the wastewater entering the marine environment is less dense, it will tend to remain on the surface and, thus, its movement is strongly influenced by surface currents. To measure surface currents, a series of drogue tracking experiments were conducted. Positions of the drogues in time were obtained using a handheld GPS unit that stored the data for later differential correction. It was found, as expected, that the surface currents are strongly influenced by the local wind conditions.

6. WATER QUALITY TESTING METHODOLOGIES

Four major water quality parameters were tested during the project for use in determining the dispersion of wastewater entering Shannon Bay. The parameters monitored were ammonia, phosphorus, bacteria speciation and counts, and biochemical oxygen demand (BOD). This was a slight deviation from our original plan of measuring total Kjeldhal nitrogen (TKN) in addition to the above parameters. After performing several lots of TKN analysis, it was found that it was too time-consuming and results were highly variable and thus lacked reliability. It was decided to halt this testing in favour of a more comprehensive focus on the other parameters.

When the water sampling in Shannon Bay commenced in mid-December there was an ice cover of approximately 1 m thickness. Ten holes were drilled through the ice using a Jiffy Drill to allow sampling to proceed. Water samples were collected using a Niskin bottle, at a depth of 3 m below the surface. One set of samples was also taken 3 m above the ocean bottom for comparison. The samples were transferred to sterilised 1 L glass Schott bottles for transport to the lab and storage. Warming temperatures and strong winds resulted in the breakup of large parts of the ice cover by 24 December, requiring a change in sampling techniques. Samples were collected directly into Schott bottles from Shannon Bay using either a Zodiac or the Southern Comfort from 24 December through to the end of the program on 8 January. The location of each sample was determined using differentially corrected GPS fixes. The breakup of the ice cover allowed sampling adjacent to the shoreline where the wastewater entered the marine environment. Immediately after collection, the samples were transported to the lab at the station and were refrigerated. Analysis usually began within several hours of collection.

Ammonia analysis was conducted on the collected samples with no filtration or pre-treatment. Standard method 4500-NH_3 was followed for the Phenate Method using a spectrophotometer to measure absorbence at 640 nm (APHA 1995).

Like the ammonia analysis, phosphorus analysis was performed on unfiltered samples. Again, Standard Method 4500-P was followed for acid hydrolysis and the Stannous Chloride Method. There were no problems encountered with the methodology and the results appear to be reasonable.

BOD analysis was conducted using standard BOD bottles with dilutions of 1:1 and 1:2 (sample : dilution water) for all marine samples. Dissolved oxygen concentrations were measured using a standard DO probe and meter. The results of the BOD tests were inconclusive and are, therefore, not reported. There was no identifiable variation in BOD between any samples due to the low amounts of digestible material in the samples.

Bacteria counts were conducted on each sample collected using the membrane filtration method. Merck Chromocult agar was used as the substrate allowing differentiation between four groups of bacteria on a single filter. The four groups of bacteria were total coliforms, E. coli, generic gram negative bacteria, and some strains of Shigella, Yersinia and Salmonella bacteria. There was some difficulty differentiating between the E. coli and the more general total coliform groups of bacteria due to similar colourations, hence total counts are reported. Counts were conducted at 24 and 48 hours for most samples collected. It was found that in some samples, there was little bacterial growth after the initial 24 hour incubation, likely due to the cold seawater (−1.8°C) environment in which the bacteria were residing. It may take longer for the bacteria to become active and grow after being exposed to the cold.

The primary aims of these experiments were to determine the spatial and temporal extent of contaminants discharged from the sewage outfall servicing Casey Station. The specific questions asked and null hypotheses (NHs) examined were:

Q1: What spatial differences in selected water quality variables occur in Shannon Bay resulting from the discharge of treated effluent?

NH1: There are no differences in the concentration of contaminants among sites within Shannon Bay.

Q2: What effect does the ice cover have on concentrations of selected water quality variables at sites within Shannon Bay?

NH2: There is no difference in the concentration of any contaminant at any site within Shannon Bay for the times before the ice moved out of the bay and for the times after the ice had moved out of Shannon Bay.

This was achieved by subjecting the data to an analysis of variance. Analysis of variance has numerous properties that make it ideally suited to detecting impacts. Some are:

- The analysis is able to break up the 'noisy' data into discrete and useful packages. For example, variation associated with changes that occur as a result of the human disturbance (i.e. the impact), naturally-occurring spatial and temporal variation, and the various combinations thereof can be identified.
- The technique allows specific statistical tests to be derived for the various packages.
- All the various sources of variation (packages can be incorporated into a single analysis and this reduces the chances of error.
- The likelihood of the error can be calculated for various scenarios.

- The results from analysis of variance do no suffer greatly through departures from the underlying assumptions of the technique.

It was assumed that the variation of a particular contaminant at a particular site was dominated by differences in concentrations that occur on different sampling days rather than *bona-fide* replication of samples. We believe this assumption is valid for the following reasons:

- There is large variability in the concentration of contaminants in the effluent. This variability is much greater for time scales of hours or longer, rather than short time scales.
- The effluent discharge is intermittent. Therefore the system variability will be naturally greater due to the presence/absence of the effluent.
- The system is dynamic and dominated by time scale of the order days, rather than seconds.
- Previous experience indicates that the variation due to replication of samples is an order of magnitude less than that due to sampling carried out on different days.

Simultaneous statistical tests (F-tests) were carried out using adjusted values of the various components of the variation (mean squares) and the results of these tests were used to determine whether sites or times are significantly different. For all tests, significance was calculated to be at the 5% level (ie. a 1-in-20 chance or error).

7. RESULTS FOR SHANNON BAY

Eighty-two water samples were drawn from Shannon Bay and analysed during the period 15 December 1997 to 8 January 1998, with additional samples collected at a variety of other marine locations for comparison. In addition, several sets of samples were collected from the influent equalisation tank and the effluent retention tank of the waste treatment package plant. The water samples collected in Shannon Bay represent both a temporal and spatial distribution that can be evaluated in several different ways. Initially, we have chosen to look at the spatial aspect of the water quality parameters, ignoring the fact that the samples were collected over a 24 day period.

Before presenting the results for the samples collected from Shannon Bay, it is beneficial to report the results of the water quality testing of the influent equalisation tank and the effluent retention tank for comparison. Samples were collected on several days over the project period, and on one day, were collected every two hours from 9.00 am until 4.15 pm. These results are presented in Table 1.

Table 1.
Ammonia, Phosphorus and Bacteria Concentrations in the Casey Station Wastewater Influent and Effluent

Date (Time)	Sample	Ammonia (mg/L)	Phosphorus (mg/L)	Total Bacteria (cfu/100 mL)
15/12 (17.15)	influent	3.86	5.50	>100,000
15/12 (17.15)	effluent	2.29	13.86	77,000
1/1 (11.00)	influent	2.20	10.40	6,000
1/1 (11.00)	effluent	0.95	10.64	660,000
6/1 (9.00)	influent	1.71	10.85	
6/1 (9.00)	effluent	1.43	10.80	412,000
6/1 (11.00)	influent	1.74	12.39	24,000
6/1 (11.00)	effluent	1.47	8.58	402,000
6/1 (13.00)	influent	2.22	9.65	59,000
6/1 (13.00)	effluent	2.27	9.47	346,000
6/1 (16.15)	influent	1.94	13.32	271,000
6/1 (16.15)	effluent	1.65	3.36	208,000

As seen in Table 1, levels of ammonia vary from 1.7 mg/L to over 3.8 mg/L in the influent and from 0.95 mg/L to over 1.4 mg/L in the effluent. Levels of phosphorus are significantly higher in both the influent and effluent flows, varying from 5.5 mg/L to 13.3 mg/L in the influent, and from 3.36 mg/L to 13.86 mg/L in the effluent. Bacteria counts are also seen to be significant, varying from over 660,000 cfu per 100 mL (effluent) to less than 6,000 cfu per 100 mL (influent). There are significant variations for all parameters that are likely due to the day and the time of day the samples were collected, and the intermittent throughput of the treatment plant.

As mentioned previously, over 80 samples of seawater were collected from Shannon Bay over the 24 days available. A portion of these samples were taken from holes bored in the ice, while the remainder were taken from a boat, and thus the locations were not identical over the study period. The location of the samples taken through the ice are shown in Figure 2. Contour plots of the mean concentrations of ammonia, phosphorus and total bacteria counts are shown in Figures 3, 4, and 5, respectively. At locations where duplicate samples were obtained the data was averaged to provide a single value as required by the software used (SURFER). A linear kriging methodology was used to determine spatial averages and develop the grid upon which the contours were based. Data collected adjacent to the shoreline after the breakout of the ice in late December was not used to develop the plots shown in Figures 3-5 since there was no data for the shoreline locations when the ice was present.

It should be noted that the ranges of values for ammonia, phosphorus and bacteria are significantly lower for the samples collected from Shannon Bay than the effluent values shown in Table 1. This result is expected due to mixing and dilution. The measured ammonia levels in Shannon Bay vary from 'not detected' to slightly over 0.2 mg/L. (Note: a value of 0.69 mg/L was measured, but the validity of the data point is somewhat in doubt.) The range for phosphorus was somewhat greater, again ranging from 'not detected' to over 3.8 mg/L. The bacteria counts range from 0 to over 1600 per 100 mL. Several samples had significantly higher counts but no exact number can be given due to difficulty in identifying individual bacterial colonies.

The data presented above removes the temporal variation that may be in the dataset since it is averaged in the spatial domain only. It is more difficult to determine the temporal variations in the data since it was not strongly considered in the field data collection design. Initially, all sampling was done at fixed locations through holes in the ice but, upon ice breakup, no methodology was put in place to allow continued sampling at the same locations. To facilitate an analysis between the data collected when an ice cover was in place and after the ice drifted out of Shannon Bay, samples collected after 24 December were assumed to be collected from the location of the nearest borehole in the ice. The error in measurement even with post-processed GPS location data made this assumption reasonable. (The entire dataset was also analysed without grouping into the ten discrete locations, and similar trends in the data were seen.) Figures 6, 7, and 8 separate the mean concentrations of ammonia, phosphorus and total bacteria counts in Shannon Bay into periods with and without ice cover. It is seen that there is a significant difference between the two periods.

Figures 9, 10, and 11 illustrate a second approach for looking at the Shannon Bay data to find time-dependent trends. In these figures the values for each of the ten routine sampling sites are plotted for each day samples were collected. A clear trend of higher values for each parameter is seen in the Figures 9, 10 and 11 from day 29 onward. Peaks in the data occur on day 31 for ammonia and phosphorus and on day 39 for the bacteria. The peaks in ammonia and phosphorus correspond to the 31st of December (day 365 in Figure 12) that is seen to be the warmest day of the sampling period as shown in Figure 12. The peak bacterial count was on day 39 (day 373 in Figure 12). Though the experiment was not designed to evaluate temporal trends, the data does indicate a trend of increasing ammonia, phosphorus, and bacteria from the beginning of the project through to its end in early January.

Table 2.
Analysis of variance results comparing sites. The mean concentration is numerated below the site number

Ammonia

Site number	9	8	7	10	3	5	4	1	2	6
Mean	0.0037	0.0090	0.0104	0.0117	0.0147	0.0263	0.0286	0.0414	0.0471	0.0925

Phosphorus

Site number	4	9	8	7	5	3	6	2	1	10
Mean	0.116	0.304	0.492	0.516	0.554	0.622	0.678	0.703	0.821	0.846

Bacteria

Site number	5	10	9	7	8	6	4	3	1	2
Mean	1.13	1.17	1.28	1.43	1.44	1.67	1.80	2.73	3.81	4.87

Notes related to Table 2.

- Analysis of variance used to compare differences among the ten routine sampling sites. Significance determined at the 5% level.
- Results presented in Table 2. (See Figure 2 for sample site location numbering).
- Sites arranged in increasing order of the mean value.
- The underscore among sites indicates "no significant difference".
- Sites closest to the outfall have the highest concentration of ammonia, phosphorus and bacteria.

Table 3.
Significance of ice cover in Shannon Bay.

Site #	Ammonia	Phosphorus	Bacteria
1	NSD	NSD	✓
2	✓	✓	✓
3	✓	✓	✓
4	NSD	NSD	✓
5	NSD	✗	✓
6	✓	✓	✓
7	✓	✓	✓
8	✓	✓	✓
9	✓	✓	✗
10	✓	✓	✓

✓ = concentrations without ice cover exceed concentrations with ice cover.
✗ = concentrations with ice cover exceed concentrations without ice cover.
NSD = no significant difference at 5% level.

Table 3 presents the results of an analysis of variance that compares the concentrations of each of ammonia, phosphorus and bacteria before and after the sea-ice moved out of Shannon Bay. The ticks indicate that the concentration of the contaminant was significantly greater after the ice cover was removed while the crosses indicate that the concentrations of the contaminant was significantly greater before the ice moved out of Shannon Bay. Significance was taken at the 5% level. The results show significantly higher concentrations of contaminants in the waters of Shannon Bay without the ice cover for all contaminants and at most sites.

8. RESULTS FOR OTHER LOCATIONS

Samples were collected from a variety of locations outside Shannon Bay for comparison and to determine background levels. A group of samples was collected from the ocean at the Adelie penguin rookeries at Whiney Point and at Shirley Island. In addition samples were collected from Brown Bay and from the ocean about 1 km north of Shirley Island. The analyses of these samples are shown in Table 4.

Table 4.
Ammonia, Phosphorus and Bacteria Concentrations for Whitney Point (WP), Brown Bay (BB), Shirley Island (SI), and Several Ocean Sites away from Land

Date	Sample	Ammonia (mg/L)	Phosphorus (mg/L)	Total Bacteria (#/100 mL)
22/12	WP	0.01	0.09	0.4
22/12	WP	0.02	0.07	0.4
22/12	BB	0	0.06	0
22/12	BB	0	0.08	0
22/12	SI	0	0.09	0
22/12	SI	0		0.8
2/1	SI	0.34	1.70	0.8
2/1	SI	0.44	3.65	0.4
2/1	Ocean	0.12	1.00	0
2/1	Ocean	0.07	0.78	10
6/1	Ocean	0.09		0
6/1	Ocean	0.01		0

The data in Table 4 indicates relatively low levels of ammonia, phosphorus and bacteria in all but the two samples taken at Shirley Island on 2 January 1998. These samples were collected adjacent to a penguin nesting area where the birds entered and left the water. Melt water was flowing from the nesting area, along the tracks the penguins were following, into the small bay where the samples were obtained. Earlier samples at Shirley Island were taken at the same location, but no melt water was present at that time. The Whitney Point samples were also taken when there was little or no melt water flowing into the ocean.

9. METEOROLOGY

Since meteorology plays a key role in the movement of water in Shannon Bay and in the melting of the snow mass into which the wastewater discharges, it is important to see how temperatures and wind speed varied during the study period. Figure 12 contains the ten minute average wind speed data for the study period. It is seen that winds average about 4 m/s except during periods of storms when it can exceed 30 m/s. No samples were collected during the windy periods due to the breaking up of the ice cover and poor visibility. Therefore, it is difficult to determine the effects of high winds on water quality. The effects of wind on the bulk water movement are described in detail in Cathers et al. (1998).

The second meteorological variable of interest is the air temperature. It had an influence on the rate of melting of the snow mass that sits above Shannon Bay and through which the wastewater flows after exiting the discharge pipe. The ten minute average temperatures for the period is given in Figure 13. It is seen that the temperature was increasing from 15 through 30 December and begins to decrease after that date, but remains higher than in mid-December. This trend in daily temperatures is similar to the trend seen in the ammonia and phosphorus data from Shannon Bay.

10. WATER USAGE

Records of water usage at Casey for the year 1997 were obtained from the plumber to obtain an idea of annual throughput of the wastewater treatment plant. The available records only had water usage tabulated on a monthly basis, thus hourly, or even daily loadings were unknown. The monthly water usage for the 1997 year is shown in Figure 14. Usage varies from a low of 55,000 L in May to 186,000 L in December. Translating these into average daily figures, usage varies between 1,774 L to 6,000 L per day. This is significant because the maximum design flow for the wastewater treatment plant is 6,000 L/day. If the maximum design flow is exceeded, it is likely that output water quality will begin to decrease due to less than adequate residence time in the system.

11. DISCUSSION OF RESULTS

The results of this project presented above raise a number of discussion points that will be addressed in detail in this section. First, let's focus on the wastewater treatment plant since it is early in the system. The facility appears to be operating well, but at times during peak water usage is probably being overloaded to a small extent. This is likely not problematic, but water usage should be monitored to determine if it is increasing and if overloading of the rotating biological contactor is frequently occurring. If this is the case, monitoring of effluent quality should probably be initiated to ensure that discharges are within the acceptable range. Though no level has been officially established for the Antarctic, the Division may have standards that it elects to follow. In general, the system appears to be working well and provides a level of treatment that is significantly greater than at other stations in the Antarctic.

The second point of discussion is the water quality found in Shannon Bay based upon the sampling and analysis conducted as part of this project. From the figures presented in the results section, there appears to be both spatial and temporal variations in ammonia, phosphorus and bacteria levels in the Bay. As seen in Figures 3, 4, and 5, there appears to be higher concentrations near the southern and eastern coastlines of the Bay. This is consistent with the point of wastewater discharge above the southern shoreline. After discharge from the end of the sewer pipe, the wastewater flows over rocks and possibly through snow and ice until it enters the marine environment. The actual point that the wastewater enters the bay is not known, nor is it known if it is a single stream or if it is dispersed along the coast. Also, the amount of dilution that may occur as it travels to the Bay is not known, nor is the travel time from the pipe end to the water. Since the wastewater is not directly discharged into Shannon Bay and since it is not a continuous discharge, it is reasonable not to see a typical plume type pattern of concentrations. Thus the concentration distributions seen in Figures 3, 4, and 5 are reasonable.

The concentration distributions seen in Figures 3, 4, and 5 tend towards a linear type structure parallel with the southern shore of Shannon Bay for ammonia and bacteria, and the eastern shore of the bay for phosphorus. This linear structure is consistent with a possibly distributed discharge along the southern coast and with the current and drogue data collected for the Bay. A linear discharge along the coast would create the linear trend since effluent would be entering the marine environment more as line source, rather than as a point source. The line source would create a gradient of decreasing concentrations in the northerly direction, as seen in the figures. The second contributor to the linear trend parallel to the coast is the prevailing currents in the Bay. Both the current meters and drogues indicate a predominantly east-west flow of water in Shannon Bay under non-storm conditions. A comprehensive discussion of these currents is contained in Cathers et al. (1998) and, therefore, will not be repeated here. This pattern of movement of water would also tend to create the linear concentration structure seen in the data.

Dilutions and Die-off

A comparison of effluent water quality and the water quality found in Shannon Bay for the three major components, ammonia, phosphorus and bacteria indicates that significant destruction, dilution or removal takes place. The maximum ammonia concentration in the effluent from the treatment plant was found to be 3.86 mg/L from the relatively few samples collected. The maximum concentration in Shannon Bay was found to be approximately 0.69 mg/L, though this concentration is somewhat in doubt due to its anomalously high value. If the concentration of 0.69 mg/L is used as a maximum there is a reduction of half an order of magnitude (3.86/0.69 = 5.6) between the effluent and Shannon Bay samples. The maximum concentration in which there is good confidence is slightly higher than 0.20 mg/L, which corresponds to an order of magnitude reduction (3.86/0.2 = 19.3) in concentration between the effluent and Shannon Bay. A slightly smaller reduction is seen in phosphorus levels, with the maximum in the effluent being 13.86 mg/L and the maximum in Shannon Bay being 3.8 mg/L (13.86/3.8 = 3.6). A much greater decrease is seen in the bacteria counts where they are consistently in the hundred thousands in the effluent, while in Shannon Bay the maximum is on the order of 1600 cfu per 100 mL of sample ($10^5/1600 = 62.5$). It should be noted that samples were not collected from Shannon Bay on the day the bulk of the samples were collected from the wastewater treatment plant. Thus, there is no direct relationship between the two sets of data, but it would be reasonable to assume that the output from the treatment plant does not vary significantly from day to day.

Ammonia

The ammonia concentrations decrease by over an order of magnitude between the retention tank in the treatment plant and sample collection in Shannon Bay. A portion of this is due to dilution by the ocean and as it travels from the discharge point to the ocean. In addition to dilution, it is likely that a portion of the ammonia is oxidised to another form that was not tested for. Without further testing, determining dilution and reaction ratios is not possible, however, if the analyses are correct, there is no more than about a 10:1 dilution between release and collection in Shannon Bay of the sample with the maximum ammonia concentration.

Phosphorus

The same comparison can be made for phosphorus concentrations in the effluent retention tank and in the samples from Shannon Bay. The maximum concentration in the effluent was found to be over 13.8 mg/L while the maximum in Shannon Bay was over 3.8 mg/L. This reduction in phosphorus is likely due to dilution only, since total phosphorus was measured and it does not readily degrade to a form that would precipitate from solution. This indicates that a dilution of about four occurs between release and the point the sample of maximum value in Shannon Bay was taken.

Bacteria

A much greater reduction in bacteria counts is seen between the effluent retention tank and Shannon Bay. The maximum count per 100 mL in the tank was over 660,000 cfu while the levels in Shannon Bay were never over 1600 cfu. This is a reduction of about 400 or 2.5 orders of magnitude. However, the bacteria are subject to die-off in addition to dilution due to the salt water and the ultra-violet light levels. The die-off rate for bacteria introduced to salt water at 0°C is approximately 36% of those present on a daily basis (Mancini 1978). Mancini has devised an empirical relation for coliform bacterial die-off that includes the effects of temperature, salinity and light intensity. In this study, data on light intensity was not available. The die-off coefficient (k) with just temperature and salinity effects included (but not light intensity) is:

$$k = (0.8 + 0.006S)x1.07^{T-20}$$

where S = salinity expressed as a percentage of seawater and
T = temperature in degrees Centigrade.

It should be noted that Mancini's relation was based on data that extended down as far as 2°C.

From the above relation we can estimate the effect of a change in temperature on the die-off coefficient as:

$$\frac{\Delta k}{k} = \ell n(1.07).\Delta T$$

The above relation will be used to estimate the die-off coefficient at 0°C (k_o) with the effects of sunlight included by basing it on a known value for t_{90} = time for 90% of the bacteria to expire. From previous outfall studies conducted in NSW, a reasonable value for t_{90} is $t_{90} \approx 6$ hours (or equivalently, $k = 9.21\ d^{-1}$). This value for bacterial die-off applies to effluent discharged to sea in daylight in water temperatures which it will be assumed are about 20°C. This die-off coefficient at 20°C is represented by k_{20}. We can now estimate k_0 that is the die-off coefficient at 0°C with the effects of salinity included as follows:

$$
\begin{aligned}
k_0 &= k_{20} - \Delta k \\
&= k_{20} - \ell n(1.07)\Delta T\left(\frac{k_0 + k_{20}}{2}\right) \\
&= k_{20} - 0.677(k_0 + k_{20}) \\
&= 0.19k_{20} \\
&= 0.19x9.21d^{-1} \\
&= 1.8d^{-1} \\
t_{90} &= \frac{\ell n10}{k_0} \\
&= 1.3d
\end{aligned}
$$

This implies that bacterial die-off is slowed down significantly in low temperatures and that after about 1.3 days, 90% of the total coliform bacteria are estimated to have died in Shannon Bay.

The discharge path and the time elapsed between the effluent being discharged from the outlet of the heated pipe to entering Shannon Bay waters is unknown. In the first stage of its passage to Shannon Bay, the effluent leaves the pipe and passes vertically into an unlit cavern in which it flows over rocks and seeps through soil, snow and ice into the Bay. In this time the effluent is not subjected to any significant light levels although its temperature will drop rapidly as it leaves the heated pipe and flows through the cavern and snow. In the second stage in which the effluent reaches Shannon Bay, it is subjected to cold temperatures, saline waters and ultra-violet light. Hence the two effects of low temperatures and high light levels on coliform mortality come into action at different and unknown times. More experiments could establish the time the effluent takes to enter the Bay but without further data it is not possible to reliably estimate the die-off rates due to these two factors.

From the bacteria counts in Shannon Bay, an estimate for the dilution is 60. Due to the high variability of the bacteria counts, this estimate could be improved by taking many samples in both the treatment plant and Shannon Bay.

The rough factors of dilution shown in Table 5 are reasonable considering the wastewater is flowing onto the surface of Shannon Bay and it is less dense and, therefore, will tend to remain on the surface. These factors significantly reduce mixing, especially when there is an ice cover or when winds and currents are low. Samples were either taken through the ice cover which was present early in the program, or on days when the winds were relatively light due to restrictions on boat usage during windy weather.

Table 5.
Dilution Factors based on Ammonia, Phosphorus and Bacteria

Water Quality Parameter	Dilution Factor
Ammonia	10
Phosphorus	4
Bacteria	60

It should be noted that the maximum levels of ammonia (discounting the 0.69 mg/L sample) and phosphorus did not occur on the same day, but this is not surprising. The sources of phosphorus and ammonia in the effluent water tend to be separate and are likely not to coincide. The bulk of the phosphorus in the wastewater comes from the detergents used at Casey for washing of dishes and clothes while ammonia is mainly a human by-product. However, the maximums of ammonia and 24-hr bacteria count did occur on the same day and in the same sample, which is reasonable since they would tend to be from the same source. Unfortunately, no samples were collected from the wastewater treatment plant on that day to see if the effluent had higher levels that would correspond to the maximums found in Shannon Bay.

Temporal Variations

Another point for discussion is the temporal variation in the concentrations of ammonia and total phosphorus, and the bacteria counts. Figures 9, 10, and 11 indicate that there is a trend of increase from the beginning of the sampling period to the end. The bacteria maximum occurs on the last sampling day, while the ammonia and phosphorus maximums occur on the 31 December, nine (9) days prior to the end of sample collection. Two major changes occurred during the sampling period that may significantly alter the movement of contaminants into and within Shannon Bay; the breakup of the ice cover between 20 and 24 December, and the steady increase in average daily temperature during the period.

The presence of the ice cover had two major influences on the samples collected from Shannon Bay that influenced the levels of contaminants found in them. First, the samples were collected further from shore, however this accounted for in the plots shown in Figures 9, 10, and 11, since shoreline data is not included. The second major factor is that the ice cover will have some influence on the migration of contaminants and the dilution of samples. The ice cover reduces mixing caused by wave and wind action on the one hand, but increases the shear stress at the ice/water interface and has some porosity into which the buoyant wastewater may be trapped. The net effect is not known, but it is anticipated that the ice cover would tend to slow the advection of the buoyant water, but increase the dispersion as it advects.

The second major factor, an increase in the average daily air temperature, may also influence the levels of ammonia, phosphorus and bacteria found in Shannon Bay. After leaving the discharge pipe, the wastewater follows an unknown path over rocks and possibly through snow and ice before reaching the Bay. This path may vary, especially in the winter months when temperatures are much lower and water usage is up to 70% lower. The lower water usage and colder temperatures may cause the hole that is melted down to the rocks during the summer to close, causing the wastewater to flow into the snow and ice above Shannon Bay. There is strong evidence that this occurs during at least part of the year. Several areas of discolouration could be seen in the snow face above the Bay in locations that would indicate that they were caused by the wastewater. One area turned green as the temperatures increased, indicating an algal bloom that would utilise the carbon, phosphorus and nitrogen of the wastewater in their growth.

As the air temperature increases, the snow and ice above Shannon Bay, which contains frozen wastewater begin melting. It is hypothesised that this process adds to the normal contaminant loading coming from the treatment plant, increasing the levels of ammonia, total phosphorus and bacteria found in the water samples from Shannon Bay compared to those taken earlier in the season. Again, the data is not available to look more deeply into this possible process since it was not considered in the design of the project.

The trend in increasing levels of ammonia, phosphorus and bacteria with increasing temperature may only be an artefact of the sampling program and the habits of the station population. Since sampling was not conducted at the same point each time and the discharge of wastewater is not continuous, the trends seen are only an indication of a possible increase in contaminant levels with temperature.

Other Sample Sites

Another area worthy of discussion is the level of contaminants found in waters taken at other locations in the vicinity of Casey Station. The data contained in Table 4 show that levels of ammonia, phosphorus and bacteria were low in the samples taken on 22 December at Whitney Point, Brown Bay and Shirley Island. This is not surprising since there was little to no meltwater present to transport wastes from the terrestrial to the marine environment at Whitney Point and Shirley Island. Even though the number of penguins in the water at the two sites was high, it is not likely that samples collected would be affected by their depositing of wastes in the water. The samples from Brown Bay should not contain high levels of the three contaminants since there is little marine life in the area and no human waste stream is flowing into the Bay.

The results from the samples taken at Shirley Island on 2 January are significantly different from those collected at the same location in December. The levels of ammonia and phosphorus are much higher and are attributed to the meltwater that was flowing into the small bay where the samples were collected. It is likely that the meltwater was flowing through the penguin guano, resulting in the transport of ammonia and phosphorus into the marine environment. The levels of ammonia found in the samples were 0.44 mg/L and 0.34 mg/L for the two samples, which is higher than any of the samples collected in Shannon Bay in which there is a high degree of confidence in the accuracy of the measured values (one sample had a concentration of 0.69 mg/L). Phosphorus levels in the Shirley Island samples were also relatively high (1.70 mg/L and 3.65 mg/L), though not quite as high as the maximums found in Shannon Bay. Since there is very little human activity in the area where the samples were collected, the levels are attributable to the penguin population at the location. This indicates that the levels of ammonia and phosphorus from native sources can be as high as those from humans in some locations. It should be noted that no samples were taken of the meltwater prior to it entering the ocean, nor were any samples of guano collected to determine if it were, indeed, the source of the ammonia and phosphorus.

The bacteria levels at all locations where samples were collected outside Shannon Bay were either zero or very low. This is to be expected in the first set of samples collected in December since there was no mechanism to transport the bacteria from land to the water. However, this does not appear to be the case for the samples taken at Shirley Island in January. There are two possible explanations for this result. The first is that the bacteria were killed or inactivated since they were exposed to ultra-violet light on land and thus did not grow when incubated. The second possible reason is that penguins do not carry large amounts of coliforms and the other bacteria that the culture media would support, thus the number of bacteria observed were low (0 to 4) at Shirley Island. Further testing could be conducted to determine if either of these explanations is valid.

The result of low bacteria levels at Shirley Island suggests that the bacteria found in the Shannon Bay samples is from the human waste stream that is entering the bay. Since the density of penguins and seals in Shannon Bay is much lower than at the location where the samples were collected on Shirley Island, it would be unlikely that the bacteria came from marine animals. This means that the marine life entering Shannon Bay is being exposed to bacteria and viruses of an origin that are not indigenous to the area or Antarctica. This creates the potential of introducing diseases into the ecosystem which are not now present and to which there are no antibodies in the systems of the animals that have may be exposed. This could be devastating to certain populations and species.

12. CONCLUSIONS

The results of this study indicate that the discharge of wastewater into Shannon Bay is not creating any major short-term effects on the environment from the viewpoint of increased nutrient loading. Though the concentrations in some samples are significantly higher than are acceptable for high quality waters, the spatial average is well below the acceptable level. However, this finding should be combined with observations of the benthic life in the Bay to determine if there are impacts that may not be attributable to ammonia or phosphorus loadings. In addition, this study only looked at levels over a 24-day period, which is a relatively short interval, and samples were not taken adjacent to the shoreline when the ice cover was in place. A longer study with more detailed sampling taking place while the ice cover is present may find that there are areas of high nutrient levels that are adversely affecting the environment.

The indication that there is no major impact on Shannon Bay from the release of nutrients is encouraging because the study found that during the period of ice cover, currents were relatively low (<5 cm/s), resulting in little water movement. Under these conditions, there is the danger of increasing nutrient levels due to a lack of flushing of the Bay. It is fortuitous that for the bulk of the time the ice cover is in place, station populations are low and, hence, discharge to the Bay is low.

Sampling of a site adjacent to a penguin rookery revealed that ammonia and total phosphorus levels were at comparable levels with those found in Shannon Bay. Therefore, it is likely that the overall impact on the Antarctic environment from human-derived nutrients is significantly lower than the impact caused by the animal life. The danger is that wastewater may be disposed of in a manner that causes localised impacts, such as in a bay that has little mixing, or without removal of the bulk of the solid fraction. Both of these events occur at some Antarctic stations of other countries, with anecdotal evidence suggesting that the impacts are major. This does not appear to be the situation at Casey Station.

Though the discharge of ammonia and phosphorus do not appear to be a matter of concern at the present time, the presence of bacteria in Shannon Bay should be. The levels of bacteria found in the Bay are much higher than those found at the Shirley Island rookery site, indicating that the bacteria is derived from non-indigenous sources. This creates the potential for the introduction of foreign bacteria into the ecosystem that may be able to survive and affect the plants and animals of the region. The potential for the introduction of lethal viruses to which the animal community has no immunity is greatly increased by the discharge of wastewater that has not been disinfected into the marine environment. This is one possible path for the introduction of the poultry virus to which antibodies have been found in penguins around Mawson Station.

A recommendation was made to the operations group within the Australian Antarctic Division to install ultra-violet disinfection systems on both the incoming potable water system and the wastewater discharge system to eliminate the spread of bacteria and viruses in the Antarctic. The use of chlorine was discouraged, particularly for the wastewater system due to its strong negative impacts on aquatic life after discharge.

13. ACKNOWLEGEMENTS

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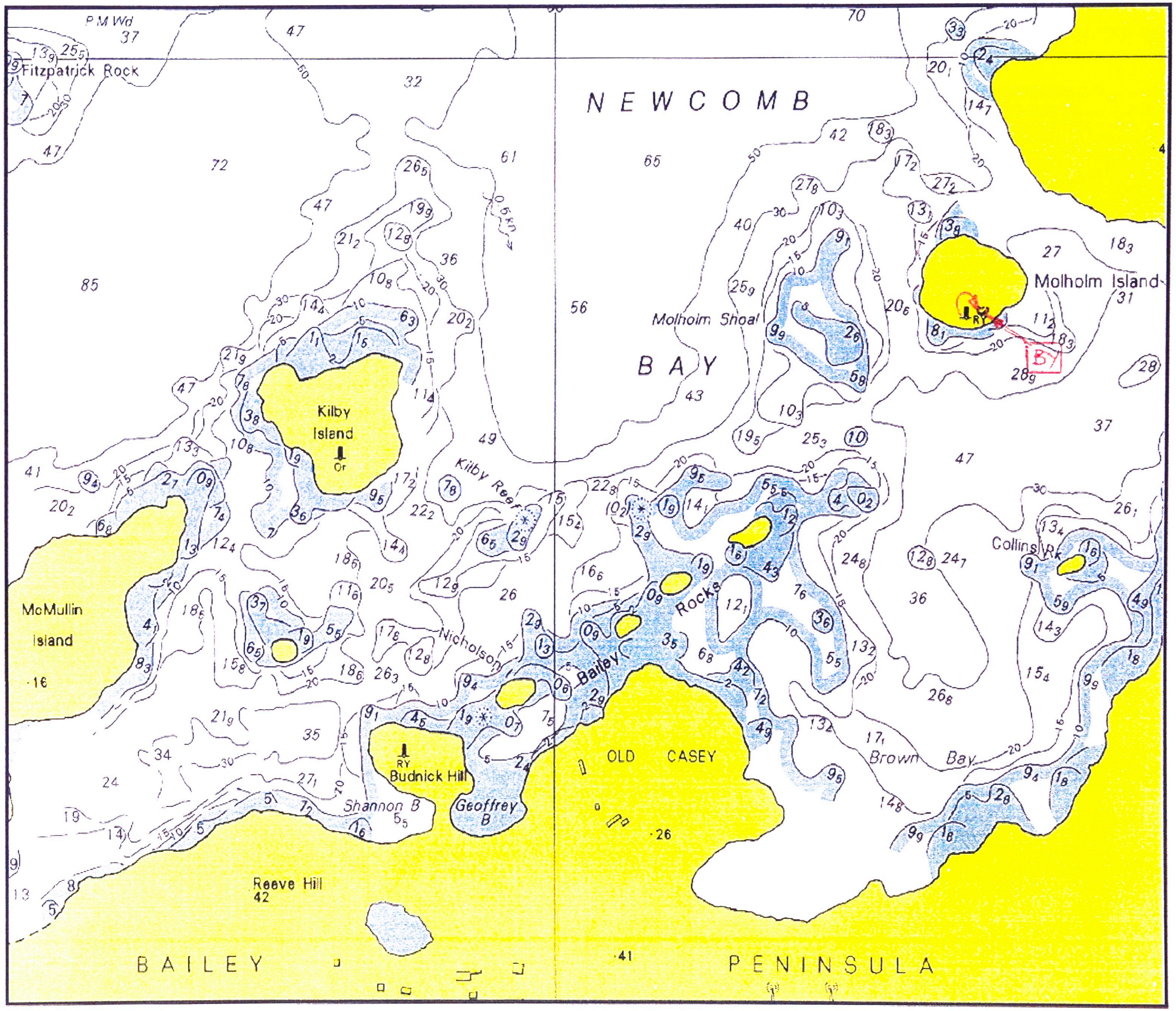
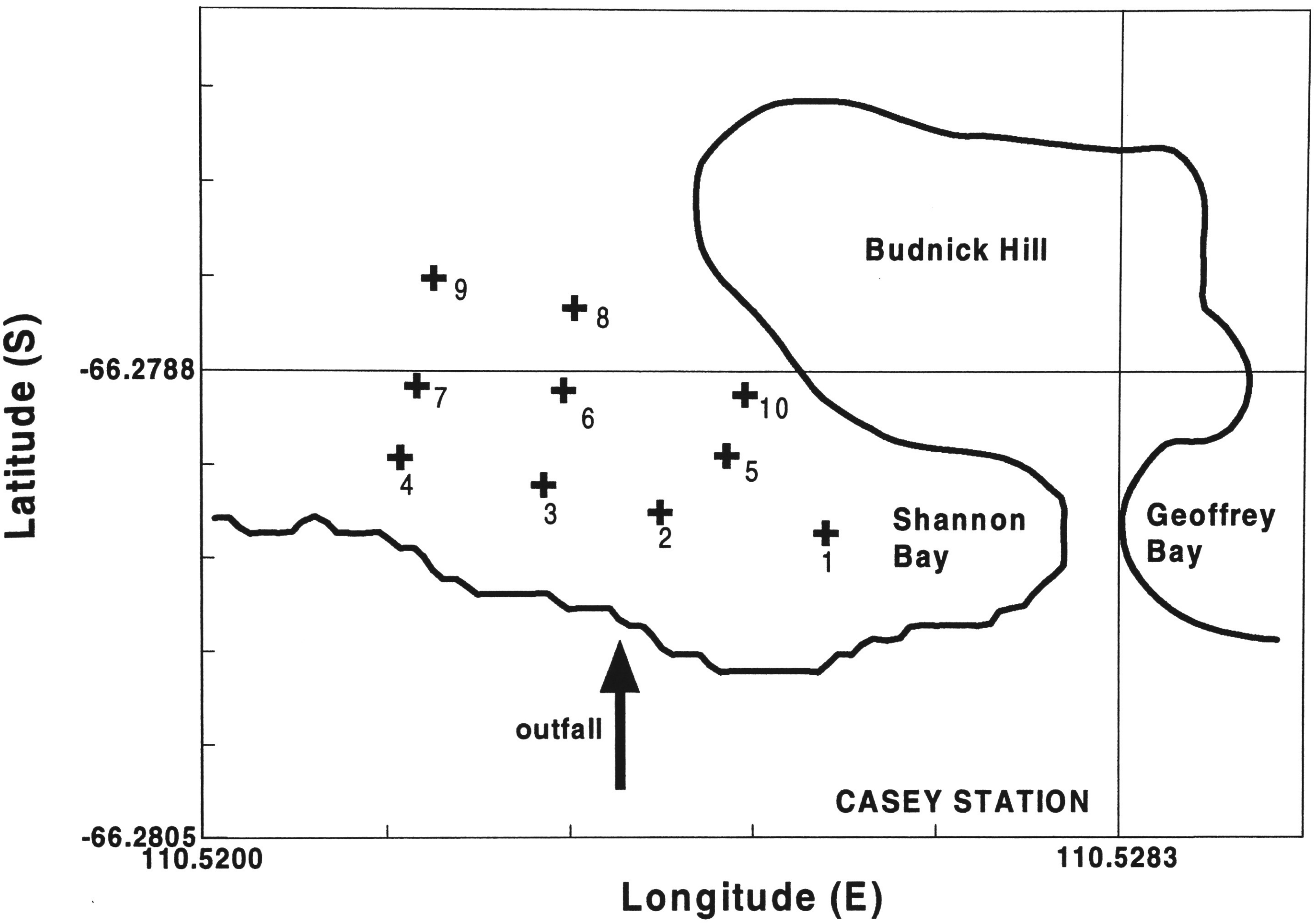


CASEY STATION AND REGION

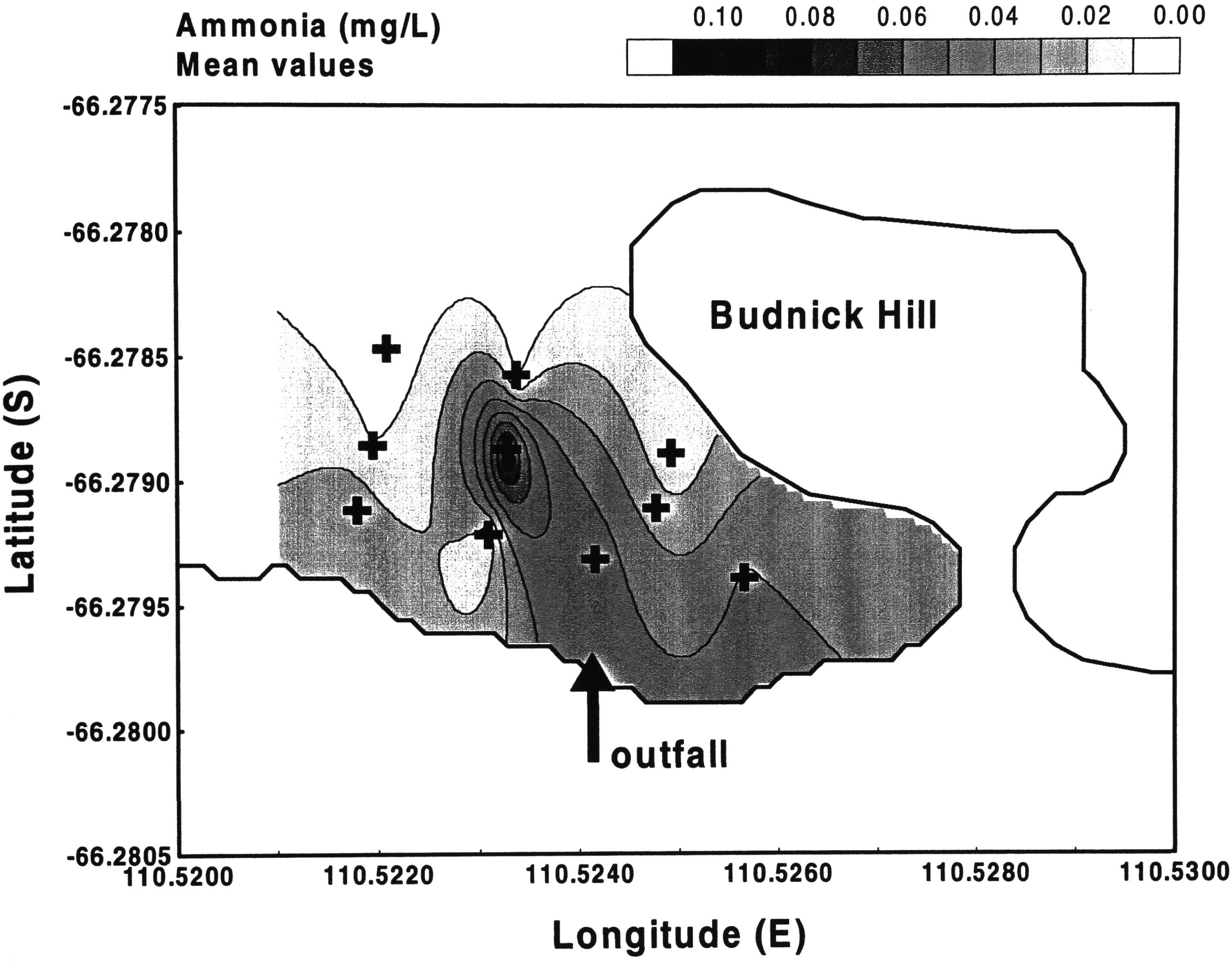
Unisearch WRL Report No. 200

Figure 1

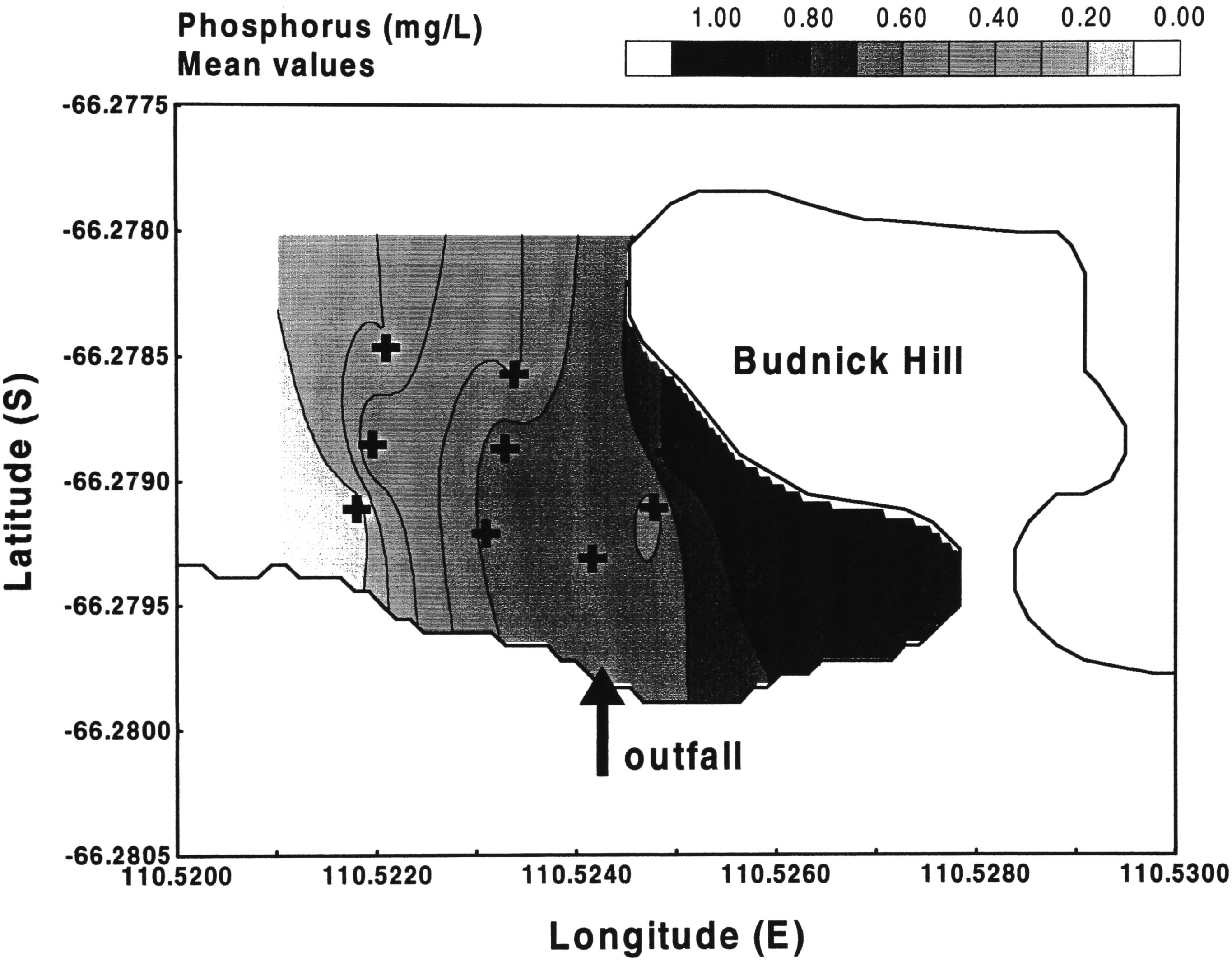
E3104M



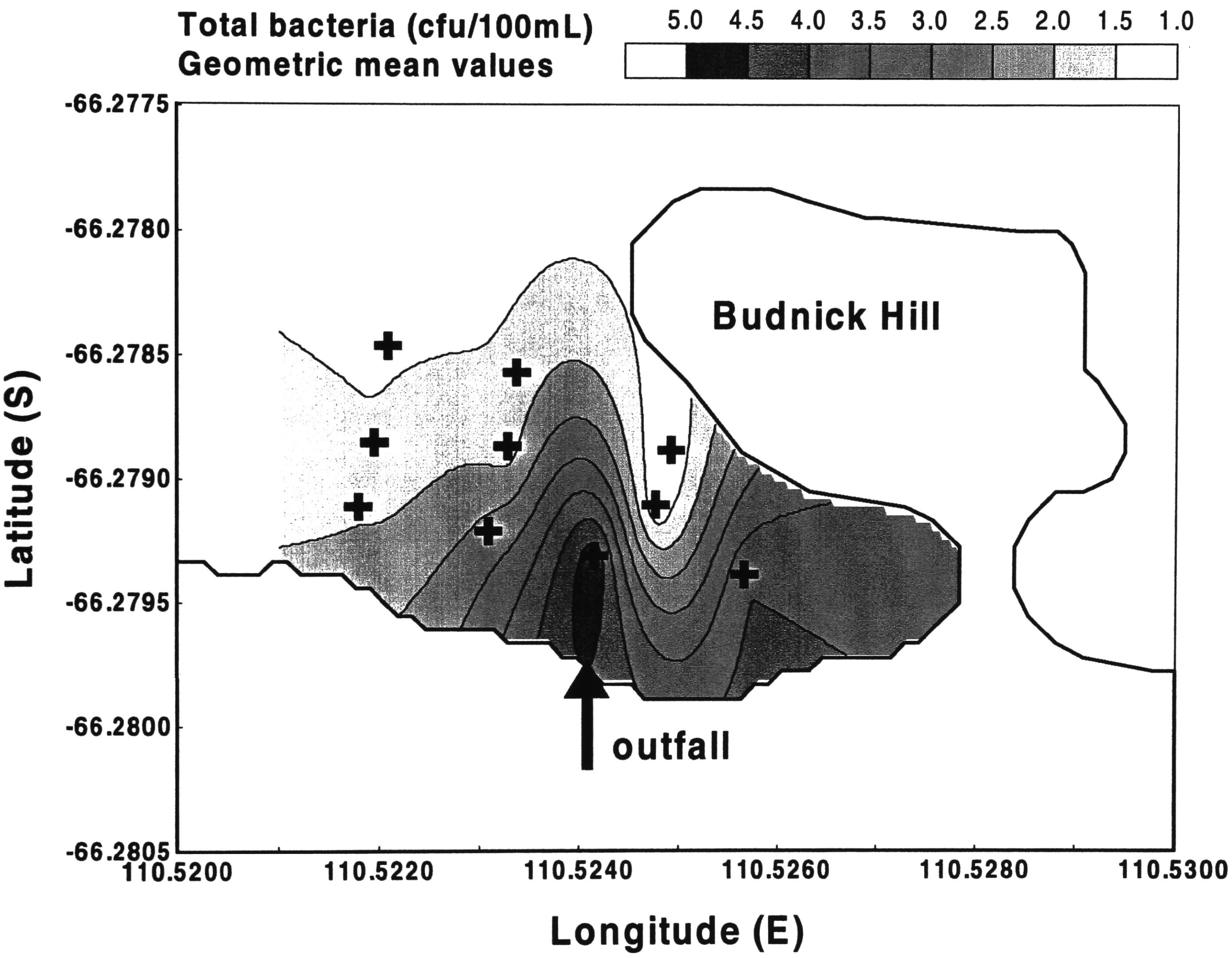
Unisearch WRL Report No. 200	LOCATION OF WATER QUALITY SAMPLING SITES IN SHANNON BAY	Figure 2
		E3104M



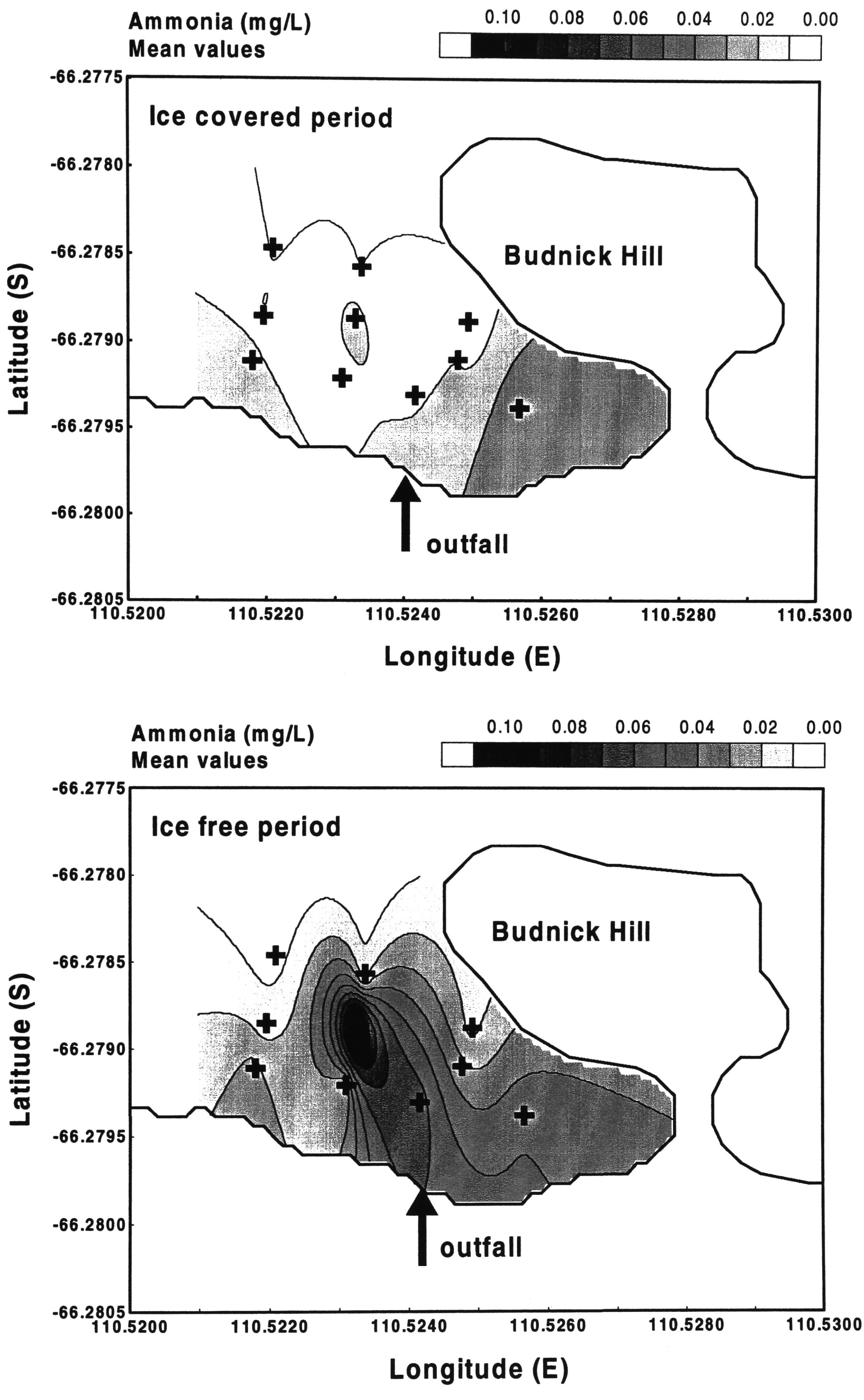
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF AMMONIA IN SHANNON BAY	Figure 3 E3104M



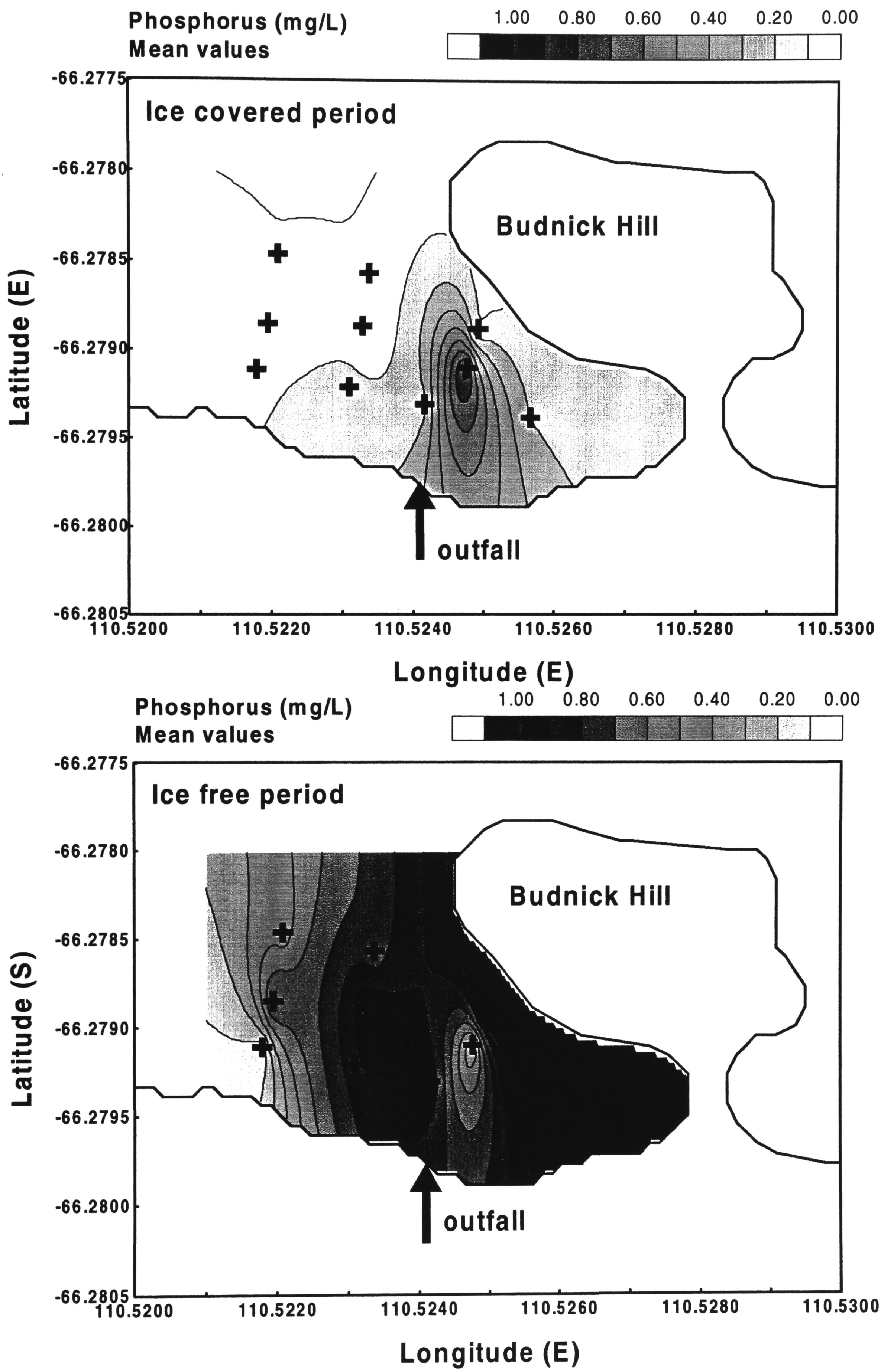
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF PHOSPHORUS IN SHANNON BAY	Figure 4 E3104M



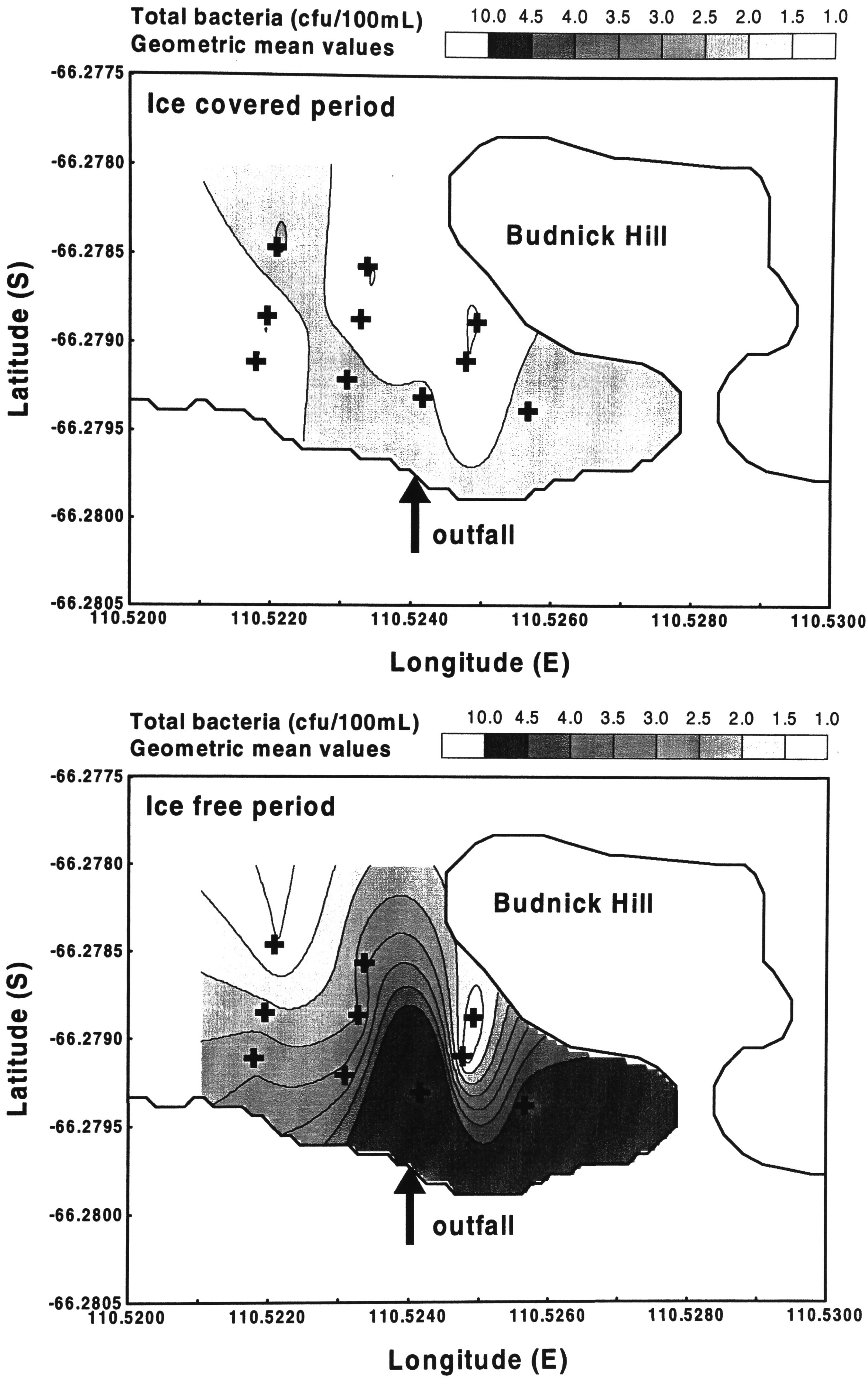
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF BACTERIA IN SHANNON BAY	Figure 5
		E3104M



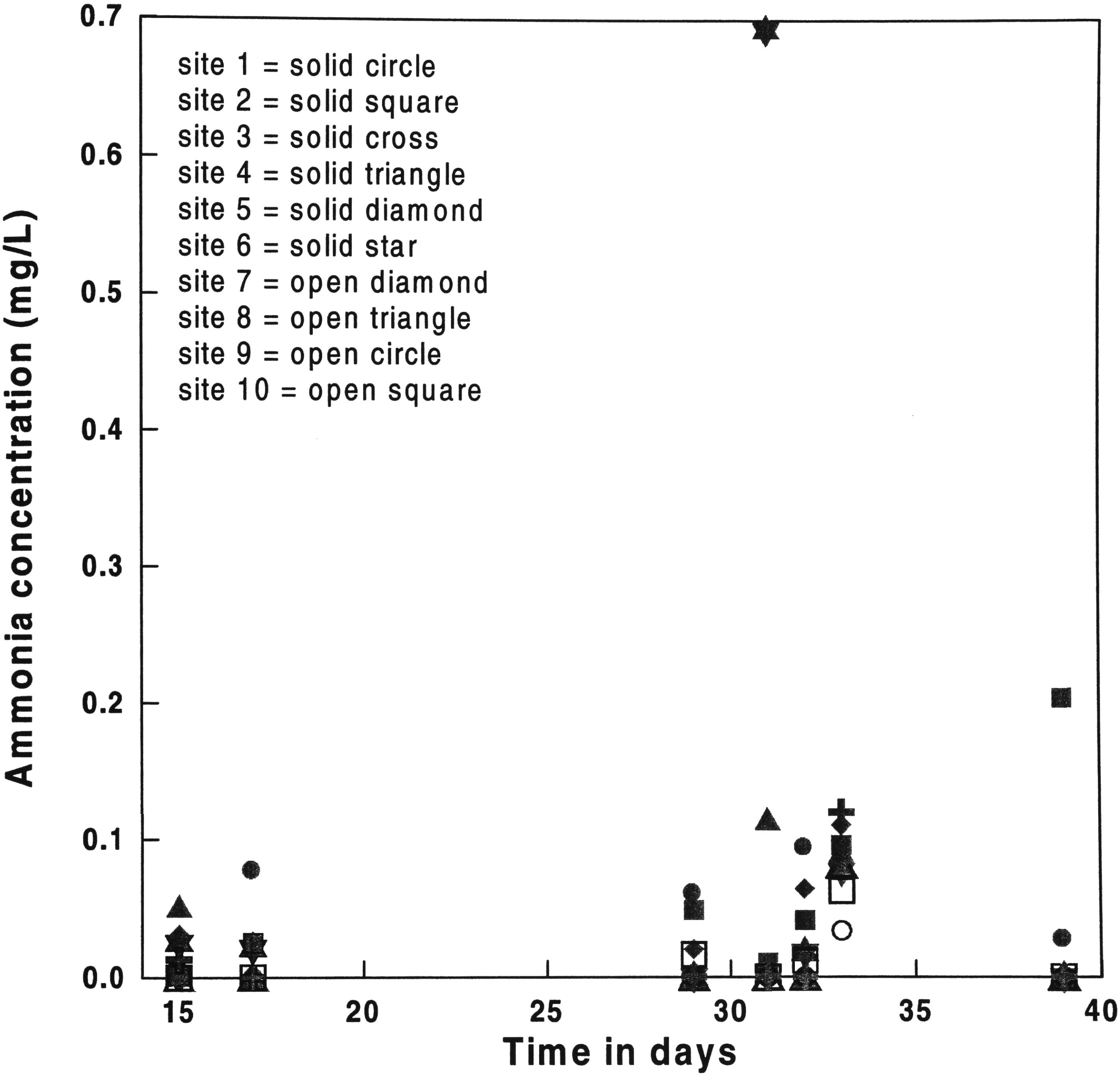
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF AMMONIA IN SHANNON BAY BEFORE AND AFTER ICE REMOVAL	Figure 6 E3104M



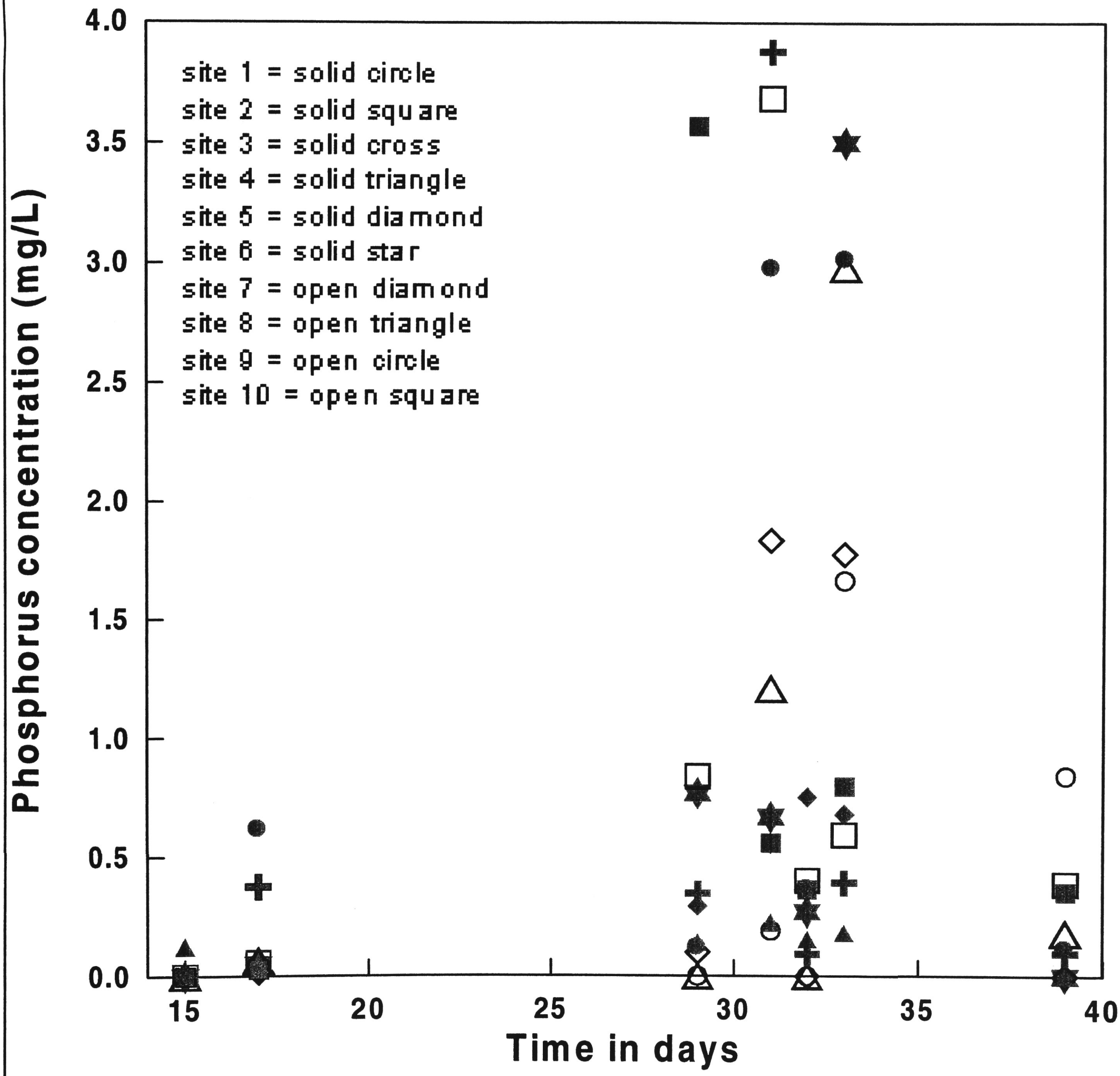
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF PHOSPHORUS IN SHANNON BAY BEFORE AND AFTER ICE REMOVAL	Figure 7 E3104M



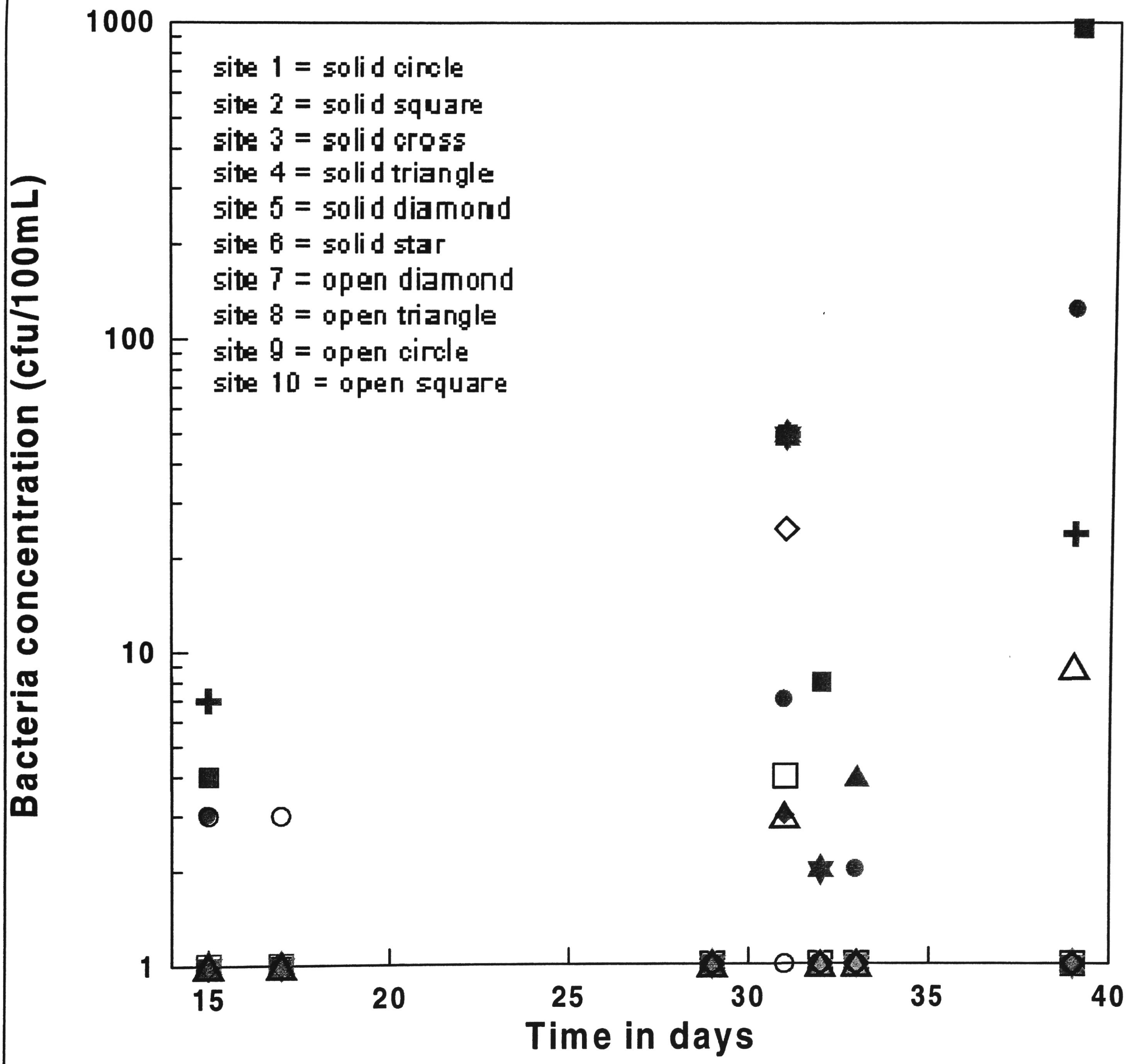
Unisearch WRL Report No. 200	MEAN CONCENTRATIONS OF BACTERIA IN SHANNON BAY BEFORE AND AFTER ICE REMOVAL	Figure 8 E3104M



Unisearch WRL Report No. 200	CONCENTRATION OF AMMONIA OVER TIME AT EACH OF THE TEN SAMPLING SITES IN SHANNON BAY	Figure 9 E3104M



Unisearch WRL Report No. 200	CONCENTRATION OF PHOSPHORUS OVER TIME AT EACH OF THE TEN SAMPLING SITES IN SHANNON BAY	Figure 10 E3104M



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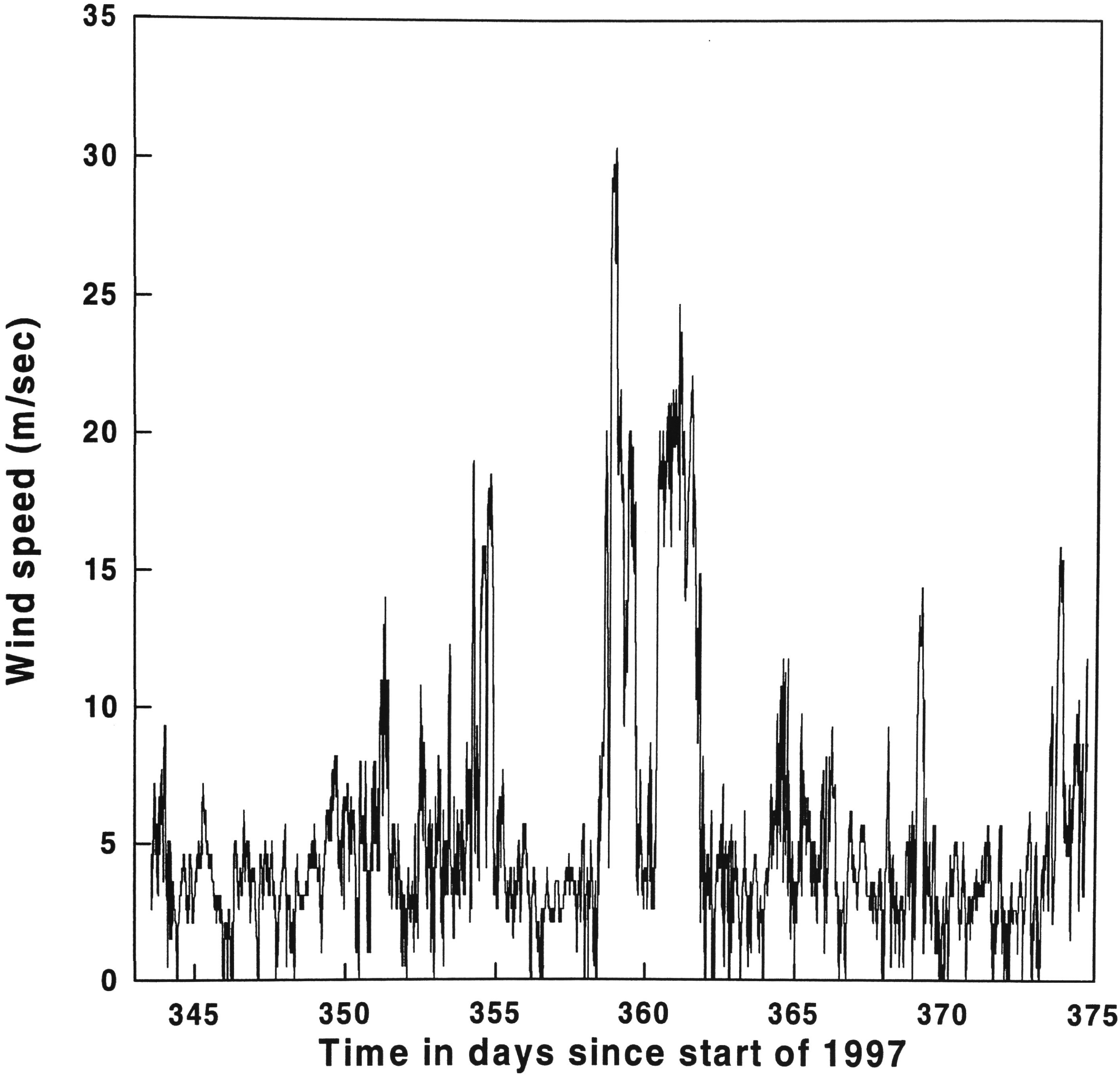
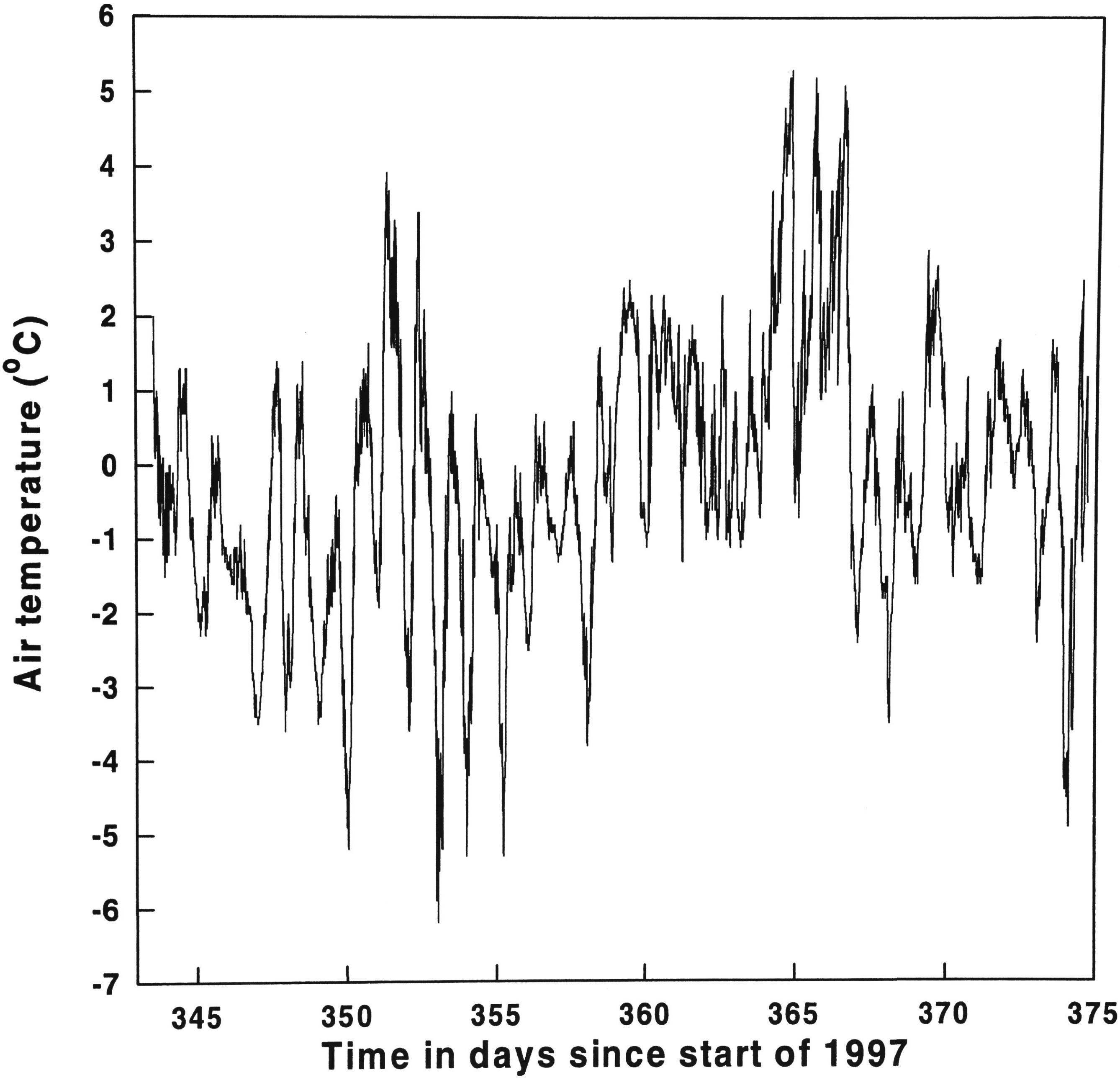
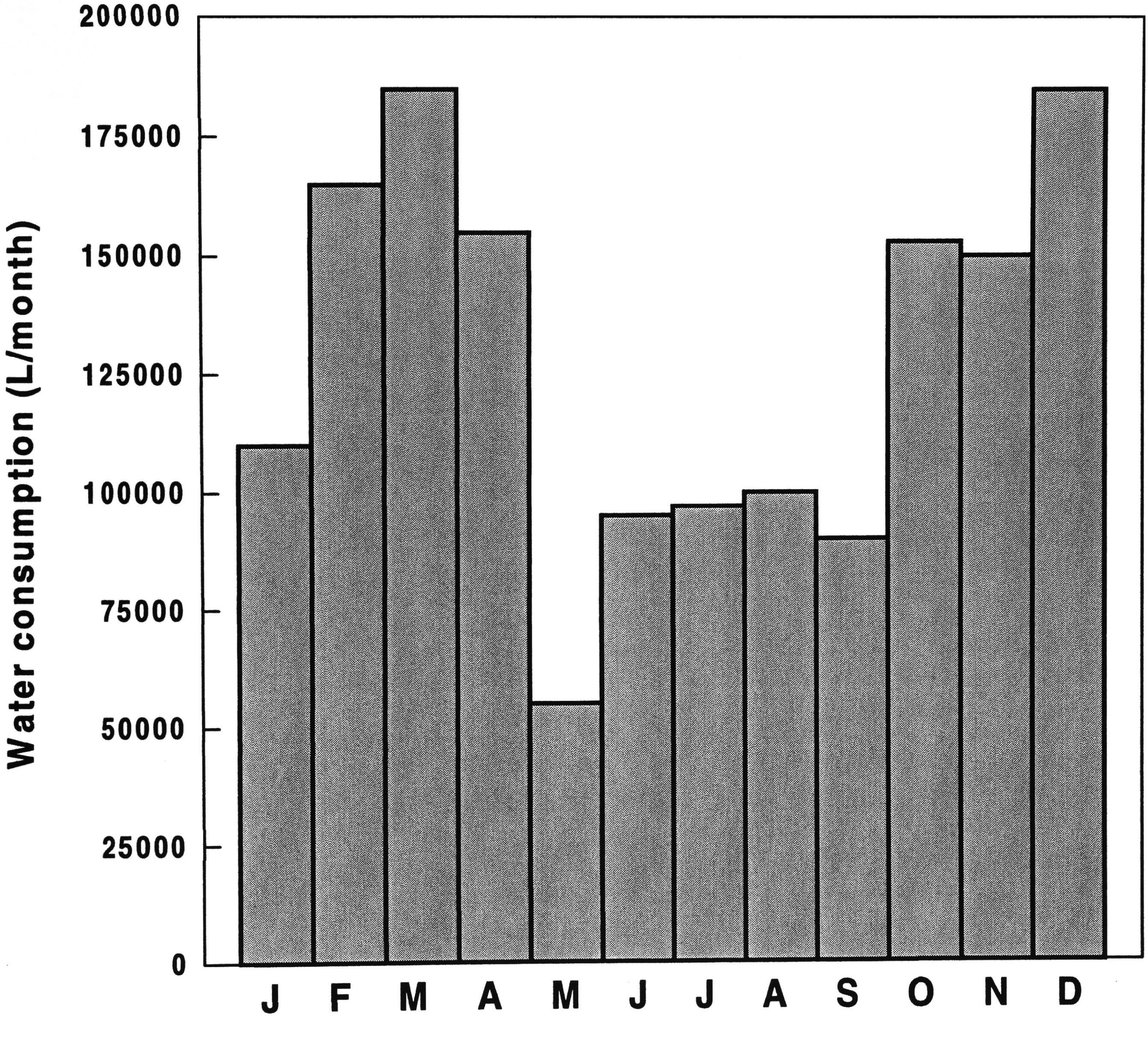


Unisearch WRL Report No. 200	TIME SERIES OF WIND SPEED AT CASEY STATION	Figure 12 E3104M



Unisearch WRL Report No. 200	TIME SERIES OF AIR TEMPERATURE AT CASEY STATION	Figure 13 E3104M



Unisearch WRL Report No. 200	WATER USAGE AT CASEY STATION DURING 1997	Figure 14 E3104M