Trophic status of St. Aubin's Bay.

1. Introduction

The States of Jersey Public Services Department (PSD) is considering options for the upgrading of waste water treatment at the Bellozanne plant. PSD is concerned that the design criteria meet the requirements of current, or proposed, European Union (EU) legislation[1], in particular the Urban Waste Water Treatment Directive (91/271/EEC) (EEC, 1991) (UWWTD), which regulates discharges to rivers, estuaries and coastal waters. The Directive aims to prevent adverse effects on the aquatic environment as a result of waste water discharge, including the prevention of eutrophication.

In February 1997, CREH was commissioned to undertake a preliminary survey to assess the concentrations of nutrients within St. Aubin's Bay. This survey was undertaken on 27th February 1997. A second survey was carried out on the 2nd April 1997 covering a larger area, to the south of the island as far as the Plateau des Minquiers and west of the island to the Plateau des Roches Douvres. The results from these two surveys were used to design a sampling protocol to be applied at regular intervals until the end of October 1997.

This report provides a summary and analysis of the results from nine sea surveys completed to 29th October 1997. In addition, seven 'beach surveys', which involved collecting sea water and catchment stream samples from the beach of St. Aubin's Bay, have been completed in the period between each full sea survey.

2. Requirements of the Urban Waste Water Treatment Directive

Council Directive 91/271/EEC (EEC, 1991) defines the standard of treatment required for waste water prior to discharge to the environment and a set of timescales for this to be achieved.

The Directive requires secondary treatment[2] as the norm for discharges of more than 2000pe[3] except under certain conditions, where either primary treatment[4] may be permitted, or additional nutrient removal may be required.

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[1] The States of Jersey are not a member of the EU and are, thus, not subject to the implementation of the Directive. However, the requirements of this and other EU Directives have been used by the States as a basis for formulating waste water treatment policy.

[2] Secondary Treatment - treatment of urban waste water by a process generally involving biological treatment with a secondary settlement (Article 1 (8)).

[3] pe - Population Equivalent. 1pe means the organic biodegradable load having a five-day biochemical oxygen demand (BOD5) of 60g of oxygen per day (Article 1 (6)).

Situations where additional treatment to remove nutrients from the effluent is required are detailed in Article 5. It is applicable to all discharges covered by the Directive. The areas where this must take place are termed "Sensitive Areas" (SAs) and criteria for their designation are detailed in Annex II to the Directive. Sensitive Areas cover three categories:

(a) freshwaters, estuaries and coastal waters which are eutrophic or which in the near future may become so if action is not taken;

(b) surface freshwaters intended for abstraction of drinking water which could contain more than the concentration of nitrate laid down under the provisions of Directive 75/440/EEC concerning the quality required of surface water intended for the abstraction of drinking water (EEC, 1975);

(c) areas where the requirements of other Directives necessitate more stringent treatment (e.g. Directive 76/160/EEC concerning the quality of bathing water (EEC, 1976).

Treatment requirements for discharges to sensitive areas are detailed in Annex IB of the Directive. For those waters falling in category (a) above, requirements are reproduced in Table 1.1.

Table 1.1: Requirements for discharges from treatment plants to sensitive areas which are subject to eutrophication. One or both parameters may be applied depending on the local situation. The values for concentration or for the percentage reduction shall apply. (Source: EEC, 1997; Annex I, Table 2)

PARAMETERS	CONCENTRATION	MINIMUM PERCENTAGE REDUCTION *	REFERENCE METHOD OF MEASUREMENT
Total Phosphorus	2 mg/l P (10,000-100,000 pe) 1 mg/l P (more than 100,000 pe)	80	Molecular absorption spectro-photometry
Total Nitrogen†	15 mg/l N (10,000-100,000 pe) 10 mg/l N (more than 100,000 pe)‡	70-80	Molecular absorption spectro-photometry

* Reduction in relation to the load of the influent.

† Total Nitrogen means: the sum of total Kjeldahl-nitrogen (organic $N+NH_3$), nitrate (NO_3)-nitrogen and nitrite (NO_2)-nitrogen.

‡ Alternatively, the daily average must not exceed 20 mg l^{-1} N. This requirement refers to a water temperature of 12°C or more during the operation of the biological reactor of the waste water treatment plant. As a substitute for the condition concerning the temperature, it is possible to apply a limited time of operation, which takes into account the regional climatic conditions. This alternative applies if it can be shown that paragraph 1 of Annex ID is fulfilled

4 Primary Treatment - the treatment of urban waste water by a physical and/or chemical process involving settlement of suspended solids, or other processes in which the BOD5 of the incoming waste water is reduced by at least 20% before discharge and the total suspended solids of the incoming waste water are reduced by at least 50%. (Article 1 (7)).

Alternatively, the requirements in Table 1.1 need not apply in SAs where it can be demonstrated that the minimum percentage reduction through the plant of the overall load entering all urban waste water treatment plants in that area is at least 75% for total phosphorus (P) and total nitrogen (N).

It should be noted that this Directive generally prescribes the minimum level of treatment which should be applied to waste water given the size of the discharge in population equivalent and the sensitivity of the local environment to which the discharge is made, rather than setting absolute end-of-pipe or environmental compliance limits. However, the Directive stipulates that treatment should be sufficient to ensure compliance with other Directives (e.g. the Bathing Water Directive 76/160/EEC).

2.1 Application of Directive 91/271/EEC to the States of Jersey

2.1.1 Current Treatment Facilities

Waste water from the island of Jersey is subject to primary settlement and secondary (aerobic digestion) followed by ultra-violet disinfection at the Bellozanne Treatment Works before discharge into St. Aubin's Bay on the south side of the island. The capacity of the treatment works is 100,000pe at a flow rate of 600 l sec^{-1}. The mean monthly nutrient concentrations in the Bellozanne final effluent are shown in Table 1.2 (Stapleton *et al.*, 1997).

Table 1.2: Nutrient concentrations (mg l^{-1}) in the final effluent from Bellozanne sewage treatment works (Stapleton *et al.*, 1997).

	NO_3-N (mg l^{-1})	NO_2-N (mg l^{-1})	NH_3-N (mg l^{-1})	PO_4-P (mg l^{-1})
January	17.46	0.86	4.95	6.23
February	17.79	1.57	3.46	5.85
March	21.88	1.04	3.83	7.70
April	26.68	0.63	4.56	9.95
May	22.05	0.77	5.11	9.90
June	22.65	0.90	3.46	10.90
July	22.66	0.62	4.50	11.30
August	21.40	0.55	4.35	11.35
September	28.65	0.63	2.63	11.60
October	26.04	0.45	1.83	9.75
November	30.14	0.24	1.33	6.95
December	18.84	0.51	6.04	6.60

The current treatment works meet the normal requirements of the UWWTD in that secondary treatment is installed. Issues relating to "Less Sensitive Areas" (LSAs) are therefore not relevant. Thus, the remaining issue to be addressed is whether the receiving waters warrant designation as a Sensitive Area where nutrient removal may be required.

Thus, two factors are relevant: (i) whether the waters of St. Aubin's Bay display criteria of a SA; and (ii) if St. Aubin's Bay is a SA, whether additional treatment to remove nutrients is necessary.

2.1.2 Identification of Sensitive Areas

Annex II of the UWWTD details criteria for the identification of Sensitive Areas. St. Aubin's Bay may fall within sub-paragraph (a) of Annex IIA, which is quoted in summary form below:

natural freshwater lakes, other freshwater bodies, estuaries and coastal waters which are found to be eutrophic or which in the near future may become eutrophic if protective action is not taken.

The following elements might be taken into account when considering which nutrient should be reduced by further treatment:

- *(i) lakes and streams reaching lakes/reservoirs/closed bays which are found to have poor water exchange, whereby accumulation may take place.*
- *(ii) estuaries, bays and other coastal waters which are found to have a poor water exchange, or which receive large quantities of nutrients. Discharges from small agglomerations are usually of minor importance in those areas, but for large agglomerations, the removal of phosphorus and/or nitrogen should be included unless it can be demonstrated that the removal will have no effect on the level of eutrophication.*

Hence, the sensitivity of St. Aubin's Bay to eutrophication is the factor of concern. If it is demonstrated that St. Aubin's Bay is subject to eutrophication, then sub-paragraph (ii) would operate. It is unclear what constitutes both a small and a large agglomeration, although limits referred to elsewhere in the Directive suggest the capacity of the Bellozanne discharge (100,000pe) would be regarded as "large" (*c.f.* pe limits referred to in Articles 3, 4, 6, 7 and 8). Thus, the removal of phosphorus and/or N would have to be considered.

The definition of eutrophication is given in Article 1 (11) of the Directive:

"eutrophication" means the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned.

In the UK, consultation papers jointly produced by DoE, MAFF and the Welsh Office (DoE, 1992; 1993) sought to provide a more scientific definition of eutrophication which could be applied when identifying SAs. The agreed criteria to be considered in assessing eutrophication potential in estuarine and coastal waters detailed in DoE (1993) are:

- *(a) nitrate Concentrations;*
- *(b) occurrence of exceptional algal blooms;*
- *(c) duration of algal blooms;*
- *(d) oxygen deficiency;*
- *(e) changes in fauna;*
- *(f) changes in macrophyte growth;*
- *(g) occurrence and magnitude of Paralytic Shellfish Poisoning (PSP); and*
- *(h) formation of algal scums on beaches and offshore.*

(Full details of the criteria are included as Appendix 1)

Additional advice has been provided by the Comprehensive Studies Task Team (CSTT, 1994). The CSTT defines an area to be adversely affected if it is hypernutrified (i.e. has high nutrient levels in the water body) and there is evidence (or the likelihood of) eutrophication. Hypernutrification exists when predicted summer values of nutrient concentration exceed 12 mmol DAIN m^{-3} (dissolved available inorganic nitrogen (= nitrate N + nitrite N + ammoniacal N)) in the presence of at least 0.2 mmol DAIP m^{-3} (dissolved available inorganic phosphorus (= orthophosphate P)) (CSTT, 1994). However, CSTT consider that whilst hypernutrification does not present a problem in itself, harmful effects are likely if a substantial proportion of available nutrients are assimilated by phytoplanktonic algae or seaweed.

CSTT consider a region to be potentially eutrophic if both the relative rate of light-controlled phytoplankton growth exceeds the reactive water exchange rate plus the relative loss rate of phytoplankton by grazing and the predicted summer maximum chlorophyll concentration is greater than 10 mg m^{-3}. Furthermore, a region is considered eutrophic if observed chlorophyll concentrations regularly exceed 10 mg m^{-3} during summer.

The waters of St Aubin's Bay also fall within the category of a potential SA in which criteria for other Directives must be met, in particular the Bathing Water Directive (EEC, 1976). However, given the bactericidal effects of the UV tertiary treatment installed at Bellozanne, it is assumed that the criteria for compliance with faecal indicator standards of this Directive are met.

2.1.3 Additional treatment requirements

Once it has been identified that a treatment works is discharging into a SA, it is necessary to consider whether nutrient removal from the effluent stream is required. Requirements for discharges to SAs are detailed in Table 1.1 above.

The Directive stipulates that total N and/or total P[5] should either meet the fixed standards set in Table 1.1 (page 2) or meet the minimum percentage of reduction prescribed in Table 1.1. The capacity of the Bellozanne treatment works, 100,000pe, is on the threshold between permitted concentrations indicated in Table 1.1. However, the concentrations of nutrients in the final effluent from Bellozanne (Table 1.2) are greater than either standard given in Table 1.1.

2.1.4 Assessment of the Jersey situation

The theoretical application of the UWWTD to the States of Jersey can be summarised as a flowchart (Figure 1.1). The key questions are:

- Are the waters into which the discharge is made (i.e. St. Aubin's Bay) a SA?
- Does the current treatment works comply with nutrient standards laid down in the Directive?
- Will additional treatment have an effect on potential eutrophic status?

Judgement on whether the Bellozanne treatment works would require upgrading to include nutrient removal under the terms of the Directive centres on whether the receiving waters are considered a SA. This is dependent upon evidence suggesting either (i) the presence of eutrophication, or (ii) that eutrophication may develop. If it is shown that eutrophication is unlikely to develop, then St. Aubin's Bay would not to be classed a SA and current treatment levels would ensure compliance with

[5] The parameters to be considered are determined by the local situation.

the terms of the Directive. If, however, St. Aubin's Bay is either eutrophic or potentially eutrophic, then it is necessary to determine whether the current effluent quality meets the criteria detailed in Table 1.1. In such a case, no nutrient removal is required. If nutrient removal is required it should be determined whether additional treatment will affect the level of eutrophication. If no improvement in eutrophic status results from nutrient removal, then it is not necessary. However, if it does have an impact on the level of eutrophication, then nutrient removal would be required.

3. Study design and sampling protocol

The current project was designed to provide data to describe the nutrient status of St. Aubin's Bay and adjacent waters in order to identify the potential for eutrophication. Sampling and analysis is based on CSTT (1994).

To determine the potential effect of a discharge to coastal waters CSTT (1994) define three nested zones:

Zone A: a small inner zone in which discharged dissolved nutrients have a residence time of $1x10^1$ to $1x10^3$ seconds (10 seconds to 15 minutes), in which particulates may accumulate in the absence of sufficient tidal stirring, and which can be recognised by the presence of discharged nutrients at concentrations close to the minimum initial dilution. Only in this zone could the growth of attached macrophytes (i.e. seaweed) be visibly increased.

Zone B: a zone in which discharged dissolved nutrients have residence times of $1x10^5$ seconds (28 hours) or a few days, the timescale of phytoplankton growth in favourable circumstances. In UK waters nutrients are dispersed through this zone mainly by tidal movements.

Zone C: a larger region in which the residence time of water is $1x10^6$ to $1x10^7$ seconds (10 to 100 days), sufficiently long for its dissolved nutrient concentration to be increased by mineralisation of particulates. Dispersion on this larger scale results from residual circulation as well as tidal movements.

For the purposes of this study the waters within St. Aubin's Bay are regarded as representing zone B whilst those beyond the Noirmont Point-Ruaudière Buoy-Nipple Rock limit represent zone C. Clearly, the initial mixing zone of the Bellozanne outfall represents zone A.

3.1 Sampling Protocol

Two separate surveys have been completed: (i) sea surveys of St. Aubin's Bay (i.e. zones A-C); and (ii) surveys of the immediate nearshore zone (including zone A when the PSD outfall is not or only partially submerged) and inputs to the Bay (i.e. effluent from Bellozanne STW and runoff from catchments) (referred to as 'beach surveys').

3.1.1 Sea surveys

The two preliminary surveys were carried out on 27 February 1997 and 2 April 1997. Survey 1 (27/2/97) involved the collection of 34 samples from within St. Aubin's Bay and 5 samples from outside the limit of the bay. Sampling was based upon three approximately north-south trending transects, one each covering the east, centre and west of the bay. The central transect is identified at its northern extremity by the PSD outfall at First Tower and at its southern extremity by the Ruaudière Buoy.

Survey 2 (2/4/97) was extended to include waters to the south and west of the island between the Plateau des Minquiers and Plateau des Roches Douvres (Figure 3.1a). The offshore (i.e. zone C) phase of this second survey incorporated sampling along three transects: south from St. Helier harbour to Plateau des Minquiers (sample spacing approximately 3.7km (2 nautical miles)); west from Plateau des Minquiers towards Plateau des Roches Douvres; and east from Plateau des Roches Douvres towards Noirmont Point (sample spacing approx. 5.5km (3 nautical miles)). Time constraints prevented the offshore samples extending as far west as Plateau des Roches Douvres and the most westerly sampling point was approximately 9km east of the rocks. In total, 15 samples were collected along these transects. The inshore survey in St. Aubin's Bay was designed to replicate the previous survey with a central transect. Sixteen samples were collected from within St. Aubin's Bay including one sample collected from the mixing zone of the outfall (zone A).

For the remaining surveys, the decision was taken not to sample as far offshore as in survey 2. Hydrographical data, and the results from survey 2, indicated that sampling in a zone approximately 1.8 to 5.5km (1 to 3 nautical miles) to the south of the island was sufficient to encompass waters which met the criteria of zone C as defined by CSTT (1994). Therefore, the remaining surveys (surveys 3 to 9) involved approximately 15 sample sites arranged in a grid comprising two transects of 6 sites located 5.5km and 3.7km (2 and 3 nautical miles) offshore, with 3 additional sites to the south of St. Aubin's Bay between 0.9km and 2.7km (0.5 and 1.5 nautical miles) south of the Ruaudière buoy (Figure 3.1b). A further 22-25 samples were taken within St. Aubin's Bay (zone B) in a similar pattern to previous surveys, and including at least one sample from the mixing zone (i.e. zone A) of the PSD outfall.

In addition, surveys 5, 6 and 7 included depth profiles taken at selected locations to provide an indication of the presence of chemical and/or temperature stratification. Depth profiles were taken along the central transect marked by the PSD outfall and the Ruaudière buoy and along an extension of this transect a further 5.5km (3 nautical miles) to the south (Figure 3.1b).

The sea surveys were carried out at monthly intervals between the end of February and the end of October. Details of the surveys are included in Table 3.1. Beach surveys, detailed below, were also undertaken on the same day as full sea surveys.

Table 3.1: Survey details.

Survey Number and Type		Date	High Water (m)	High Water Time (GMT*)	Time of survey†	Notes
1	Full sea survey	27/2/97	10.11	08:59	09:40-17:37	First preliminary survey
2	Full sea survey	2/4/97	8.11	13:25	10:20-17:53	Second preliminary survey
3	Full sea survey	30/4/97	8.52	11:42	10:48-17:05	First survey using revised protocol
3B	Beach survey	15/5/97	7.62	12:39	09:15-11:23	First beach survey
4	Full sea survey	3/6/97	10.14	04:35	10:21-15:57	
4B	Beach survey	17/6/97	8.55	03:15	09:55-12:40	
5	Full sea survey	1/7/97	9.17	03:11	11:15-17:52	First depth profile survey
5B	Beach survey	14/7/97	7.94	12:37	13:38-15:37	
6	Full sea survey	29/7/97	8.62	14:04	10:15-17:19	Second depth profile survey
6B	Beach Survey	11/8/97	8.48	10:39	14:40-17:05	
7B	Beach Survey	27/8/97	8.17	13:35	15:15-17:14	Sea survey postponed due to inclement weather. Beach survey carried out.
7	Full sea survey	9/9/97	8.81	10:04	09:44-17:44	Third depth profile survey
8	Full sea survey	30/9/97	9.96	05:37	09:25-16:15	
8B	Beach survey	14/10/97	10.32	04:34	09:25-11:33	Effluent from Bellozanne STW being discharged from short outfall at First Tower.
9	Full sea survey	29/10/97	9.74	05:04	09:42-16:18	

* Add 1 hour for British Summer Time (BST) (30/3/97 - 26/10/97).
† All survey times are in BST with the exception of surveys 1 and 9, which are GMT.

3.1.2 Beach surveys

In addition to sampling seawater at chest depth, the beach surveys included freshwater inputs from catchments which drain into St. Aubin's Bay, the discharge from the Bellozanne outfall and the final effluent from the STW.

Sea water samples were collected from 5 locations within St. Aubin's Bay:

B1 - Victoria Pool (open sea as opposed to from within the pool);

B2 - PSD outfall at First Tower (sampled on the east side of the outfall);

B3 - beach rock/ black & white navigation mark (600m west of PSD outfall);

B4 - Second Tower ski lane (sampled to the east of the lane);

B5 - St. Aubin (sampled approx. 300m west of La Haule slip).

Samples were collected from the catchment stream outfalls discharging into St. Aubin's Bay: St. Aubin's; La Haule A and B; St. Peter's Valley; and Waterworks Valley (Wyer *et al.*, 1996). Further samples were taken from the sewage works final effluent (taken from the output of the UV plant) and from the Bellozanne stream upstream of the STW discharge point. When tidal state allowed, a sample was also collected from the PSD outfall (which discharges the combined effluent from the STW and Bellozanne stream). These samples were taken to provide an indication of inshore water quality and to quantify inputs to St. Aubin's Bay.

Construction works prevented access to the Weighbridge outfall, which drains Grands Vaux/Vallèe des Vaux, during all but the first survey. Therefore, where relevant, estimated nutrient load data taken from Stapleton *et al.* (1997) were used to represent inputs from these catchments.

During survey 8B the combined effluent from Bellozanne STW and Bellozanne stream was diverted through the short outfall at First Tower (i.e. at high water mark) due to construction works.

In addition to taking beach samples during the full sea surveys, samples were taken mid-way between the full sea surveys throughout the summer and autumn period (30/4/97 - 29/10/97). Again, details of these surveys are included in Table 3.1.

3.2 Sample treatment and analysis

Samples were collected using either the States of Jersey Harbours Department tug, the Duke of Normandy, or their smaller vessel, the Duchess of Normandy. Further samples were collected on foot from the beach and from the outfalls discharging into St. Aubin's Bay.

Water samples were tested *in-situ* for temperature, pH and dissolved oxygen. Samples intended for nutrient analysis were filtered through 45μm disposable filters and immediately placed in dark cool boxes for transport. Nutrient samples were frozen prior to dispatch in accordance with EA practice. Unfiltered seawater was collected for chlorophyll *a* analysis and the samples were again placed into dark cool boxes for transport. The filtered nutrient samples and chlorophyll *a* samples were dispatched as soon as possible after the survey to the NAMAS accredited Environment Agency (EA) laboratory in Llanelli for analysis.

Filtered samples were analysed for nitrate, nitrite, ammonia, orthophosphate and dissolved reactive silicon concentrations using segmented flow analysis based on methods set out by the Standing Committee of Analysts. Unfiltered samples were analysed for chlorophyll *a* content using spectrophotometric filtration and acetone extraction.

A composite water quality probe was used to measure *in-situ* temperature, pH, conductivity, salinity, dissolved oxygen (% saturation and concentration) and depth. A displacement water sampler was used to collect water samples from specified depths (sea-bed and mid-depth during surveys 5 and 6; and from one third-depth, two third-depth and sea bed during survey 7).

4. Results

The full results of the water quality surveys described in this report are included as Appendices II (full sea surveys) and III (beach surveys).

4.1 Sea surveys

The geometric mean nutrient and mean dissolved reactive silicon and chlorophyll *a* concentrations from zone B (i.e. within St. Aubin's Bay) and zone C (i.e. further offshore) are shown in Table 4.1 and Figures 4.1 to 4.4.

Table 4.1: Geometric mean DAIN and DAIP and mean dissolved reactive silicon and chlorophyll *a* concentrations from the sea surveys.

Survey No. (Date)	DAIN ($mmol\ m^{-3}$)		DAIP ($mmol\ m^{-3}$)		Dissolved Reactive Silicon ($mmol\ m^{-3}$)		Chlorophyll *a* ($mg\ m^{-3}$)	
	Zone B	Zone C	Zone B	Zone C	Zone B	Zone C	Zone B	Zone C
1 (27/2/97)	12.43	12.43	0.45	0.43	2.45	2.35	2.00	2.23
2 (2/4/97)	11.72	12.50	0.53	0.34	0.84	0.95	1.11	1.13
3 (30/4/97)	1.55	2.03	0.11	0.12	0.29	0.18	1.74	2.48
4 (3/6/97)	1.43	1.00	0.21	0.10	0.99	0.79	1.23	1.20
5 (1/7/97)	1.01	1.31	0.14	0.15	1.50	1.44	1.23	1.04
6 (29/7/97)	1.76	2.06	0.08	0.07	1.76	1.50	0.97	1.25
7 (9/9/97)	1.69	1.69	0.25	0.29	2.13	2.06	2.06	1.64
8 (30/9/97)	2.40	2.44	0.38	0.30	3.15	2.86	1.75	0.99
9 (29/10/97)	5.00	5.17	0.49	0.45	4.30	3.99	1.74	1.49

Table 4.1 and Figures 4.1 to 4.4 show that, during each survey, the water quality varies little between St. Aubin's Bay (zone B) and further offshore in zone C. To provide a statistical comparison of the data for zones B and C, t-tests were carried out on $\log_{10}$ transformed DAIN and DAIP data (Tables 4.2 & 4.3). It was necessary to apply a $\log_{10}$ transformation to the DAIN and DAIP data because raw data exhibited $\log_{10}$ normality. This statistical analysis indicated a significant difference in DAIN concentrations between zones B and C during survey 3 (30/4/97) (Table 4.2) and between DAIP concentrations during surveys 2 (2/4/97), 4 (3/6/97) and 9 (29/10/97) (Table 4.3). However, in all four surveys where there was a significant difference in nutrient concentrations, the geometric mean concentrations are greater in zone C (i.e. offshore).

There was a marked decrease in DAIN concentrations between survey 2 and survey 3 (Table 4.1 and Figure 4.1) which may be attributed to nutrient utilisation by the spring algal bloom. Mean DAIN concentrations within both zones B and C exceeded the CSTT (1994) winter threshold of 12 mmol m^{-3} during survey 1 whilst concentrations within St. Aubin's Bay fell to just below the threshold by the time of the second survey. In all surveys after survey 3 (end of April) the mean DAIN concentration within both zones B and C remained low, although an increase in concentrations was evident during the final survey (survey 9). This increase may be attributed to the accumulation of nutrients due to reduced uptake by phytoplankton as suitable conditions for its growth diminish.

Table 4.2: T-test results, comparison of DAIN data between zones B and C.

Survey	Zone	n	Geometric Mean	Log_{10} Std. dev.	t-value	D.F.	p
1 (27/2/97)	B	34	12.43	0.06	0.23	7	0.83
	C	5	12.43	0.04			
2 (2/4/97)	B	14	11.72	0.17	0.26	16	0.80
	C	14	12.50	0.07			
3 (30/4/97)	B	19	1.55	0.18	-2.22	28	0.04†
	C	14	2.03	0.31			
4 (3/6/97)	B	18	1.43	0.43	0.25	20	0.80
	C	13	1.00	0.63			
5 (1/7/97)	B	16	1.01	0.19	-1.77	28	0.09
	C	15	1.31	0.17			
6 (29/7/97)	B	18	1.76	0.08	-1.70	22	0.10
	C	15	2.06	0.13			
7 (9/9/97)	B	18	1.69	0.13	-0.02	27	0.99
	C	15	1.69	0.08			
8 (30/9/97)	B	18	2.40	0.19	-0.18	21	0.86
	C	15	2.44	0.06			
9 (29/10/97)	B	17	5.00	0.07	-0.75	29	0.46
	C	18	5.17	0.05			

† significant at α=0.05

Table 4.3: T-test results, comparison of DAIP data between zones B and C.

Survey	Zone	n	Geometric Mean	Log_{10} Std. dev.	t-value	D.F.	p
1 (27/2/97)	B	34	0.45	0.07	-0.18	8	0.86
	C	5	0.43	0.04			
2 (2/4/97)	B	14	0.53	0.22	2.61	25	0.01†
	C	14	0.34	0.27			
3 (30/4/97)	B	19	0.11	0.19	-0.10	30	0.92
	C	14	0.12	0.14			
4 (3/6/97)	B	18	0.21	0.43	3.76	20	0.001†
	C	13	0.10	0.12			
5 (1/7/97)	B	16	0.14	0.05	-0.79	15	0.44
	C	15	0.15	0.23			
6 (29/7/97)	B	18	0.08	0.24	0.39	28	0.70
	C	15	0.07	0.27			
7 (9/9/97)	B	18	0.25	0.07	-1.67	20	0.11
	C	15	0.29	0.13			
8 (30/9/97)	B	18	0.38	0.23	1.75	18	0.10
	C	15	0.30	0.05			
9 (29/10/97)	B	17	0.49	0.05	2.89	19	0.01†
	C	18	0.45	0.02			

† significant at α=0.05

Mean DAIP concentrations (Figure 4.2) also decrease between surveys 2 and 3 to less than 0.2 mmol m^{-3} (the CSTT (1994) threshold), although offshore DAIP concentrations had again exceeded the threshold by survey 4. Surveys 5 and 6 (end of June and end of July) displayed similar mean DAIP concentrations below the 0.2 mmol m^{-3} threshold. Since survey 6 (end of June), DAIP concentrations have increased during each subsequent survey as assimilation of nutrients by phytoplankton decreases towards the late summer.. The CSTT threshold is exceeded during the three latter surveys (surveys 7-9) in both zones B and C.

Mean dissolved reactive silicon concentrations (Figure 4.3) show a marked decrease between surveys 1 and 3 (end of February to end of April). This nutrient is utilised by the spring bloom of siliceous diatoms. Since the end of April, mean silicon concentrations have increased to a maximum of 4.3 mmol m^{-3} in zone B at the end of October.

Whilst the nutrients have been utilised by algal growth, it is encouraging that chlorophyll *a* concentrations (Figure 4.4) have not increased significantly, as would be expected under eutrophic conditions. However, it should be noted that the month of June experienced 90 hours less sunshine than the 1961-90 average. This may have inhibited algal growth resulting in lower chlorophyll *a* concentrations. A full analysis of meteorological data and their potential impact on the results of this study are presented in Appendix V.

Sea temperatures show an increase from an initial average of 8°C at the end of February to 19°C at the end of July (Figure 4.5). Between July and the end of September sea temperatures remained relatively constant at around 19°C before decreasing to 13.5°C in zone B at the end of October. Average dissolved oxygen saturation (Figure 4.6) has fluctuated between 85% and 102% between surveys. Such fluctuations can be expected and relate to diurnal cycles, degree of algal growth, weather conditions etc..

The depth profiling undertaken during sea surveys 5, 6 and 7 indicated that no stratification of temperature, salinity, conductivity and dissolved oxygen with depth (Appendix IV). At some sites, during all three surveys, there is evidence of a slight decrease in oxygen levels with depth whilst, in contrast, the most southerly profile site during survey 7 (site 8) shows a marked increase in oxygen concentrations with depth. Nutrient concentrations also show little variation with depth, with DAIN concentrations generally varying by no more than 1 mmol m^{-3} and DAIP concentrations varying by less than 0.1 mmol m^{-3} (Appendix IV). One noticeable exception to this is site 21 from survey 7 where DAIN concentrations are higher at the surface and on the sea bed than in mid-profile.

The depth profiling, however, has provided some evidence to suggest that the freshwater effluent plume from the PSD outfall is remaining buoyant, floating above the denser sea water. On the final survey (survey 7) a depth profile was conducted approximately 50 m from the visible 'boil' of the outfall (site 28). The resultant profiles are illustrated in Figure 9. Both salinity and conductivity display lower concentrations close to the surface whilst nutrient concentrations are elevated on the surface. Similar profiles of high DAIN and DAIP at the surface are also present at the site adjacent to the PSD outfall during survey 6 (site 29) (Appendix V).

4.2 Beach surveys

The sea water samples taken from the beach generally exhibit higher concentrations of nutrients and chlorophyll *a* (Table 4.4 and Figures 4.8 to 4.11) than in zones B and C. The geometric mean concentrations of DAIN exceed the CSTT 12 mmol m^{-3} threshold during surveys 1 and 2 and again during survey 9, whilst the geometric mean DAIP concentrations exceed the 0.2 mmol m^{-3} threshold during all but survey

6. Again, the high DAIN geometric mean concentrations during surveys 1, 2 and 9 can be attributed to accumulation if nutrients resulting from reduced uptake by phytoplankton during the winter months.

However, there are large variations in observed DAIN concentrations. Such variation can be expected due to the proximity of the point sources of the PSD outfall and catchment streams. DAIN concentrations (Table 4.4 and Figure 4.8) regularly exceed the CSTT threshold of 12 mmol m^{-3} at the sites to the east of Beach Rock (B3). These sites (Victoria Pool (B1), PSD Outfall (B2) and Beach Rock (B3)) have displayed very high nutrient concentrations, although these may be related to the effluent plume from the PSD outfall and/or land runoff. The remaining two seawater sites (B4 and B5) are shown to display DAIN concentrations below the CSTT threshold, although DAIP concentrations consistently exceeded the CSTT threshold (Figure 4.9). Dissolved reactive silicon concentrations are also greater in seawater sampled from the beach than in zones B and C (Figure 4.10).

Individual observations and mean chlorophyll *a* concentrations in seawater sampled from the beach (Table 4.4 and Figure 4.11) have generally remained below the 10 mg m^{-3} CSTT threshold, despite being greater than those experienced further offshore. However, surveys 6B and 7B (mid to the end of August) show chlorophyll *a* concentrations to be greater, particularly in the western half of the bay (west of Beach Rock), with the highest chlorophyll *a* concentration exceeding 20 mg m^{-3} at St. Aubin (B5). It was noted at the time of sampling that the seawater was more turbid than usual which, coupled with the higher chlorophyll *a* concentrations, suggests that a nearshore algal bloom had developed. Chlorophyll *a* concentrations exceeded the CSTT threshold at four of the five sites during survey 8 (end of September), reaching 60 mg m^{-3} at St. Aubin.

Whilst chlorophyll *a* concentrations have not been high throughout the spring and summer, there have been several occasions where algal foams have been sighted, both by the field team from this project and PSD Pollution Control staff. Such a foam was in evidence during beach survey 4, although chlorophyll *a* concentrations from this particular survey have been some of the lowest recorded from beach samples. These foams, have been limited to the water's edge and are very transient, generally, failing to last a full tidal cycle.

Table 4.4: Observed and geometric mean nutrient concentrations and observed and mean chlorophyll *a* concentrations in the nearshore zone.

		B1 Victoria Pool	B2 PSD outfall	B3 Beach Rock	B4 Second Tower	B5 St Aubin	Geometric Mean†
1 (27/2/97)	DAIN (mmol m^{-3})	31.4	51.6	37.9	–	–	39.5
	DAIP (mmol m^{-3})	1.3	3.4	0.6	–	–	1.4
	Chlorophyll *a* (mg m^{-3})	4.6	3.7	4.8	–	–	4.4†
2 (2/4/97)	DAIN (mmol m^{-3})	22.8	–	70.6	–	–	40.1
	DAIP (mmol m^{-3})	1.6	–	0.5	–	–	0.9
	Chlorophyll *a* (mg m^{-3})	5.7	–	3.4	–	–	4.6†
3 (30/4/97)	DAIN (mmol m^{-3})	3.5	17.4	20.0	3.0	2.3	6.1
	DAIP (mmol m^{-3})	0.6	2.2	1.8	0.2	0.3	0.7
	Chlorophyll *a* (mg m^{-3})	3.2	3.0	3.5	3.8	6.6	4.0†
3B (15/5/97)	DAIN (mmol m^{-3})	0.9	0.3	24.7	0.9	2.8	1.8
	DAIP (mmol m^{-3})	0.2	0.7	5.8	0.3	0.3	0.6
	Chlorophyll *a* (mg m^{-3})	1.7	4.2	1.7	3.4	5.8	3.4†
4 (3/6/97)	DAIN (mmol m^{-3})	0.4	688.5	46.0	8.6	1.3	10.8
	DAIP (mmol m^{-3})	0.3	116.9	9.2	1.7	0.3	2.8
	Chlorophyll *a* (mg m^{-3})	1.6	1.9	2.2	3.0	1.6	2.0†
4B (17/6/97)	DAIN (mmol m^{-3})	0.2	289.0	0.8	0.7	0.6	1.8
	DAIP (mmol m^{-3})	0.4	48.1	0.6	0.5	0.6	1.2
	Chlorophyll *a* (mg m^{-3})	4.1	5.6	4.4	5.2	6.2	5.1†
5 (1/7/97)	DAIN (mmol m^{-3})	60.2	0.6	1.2	5.5	0.6	2.6
	DAIP (mmol m^{-3})	12.1	0.2	3.1	0.2	0.2	0.8
	Chlorophyll *a* (mg m^{-3})	6.6	5.9	2.4	2.2	2.6	4.0†
5B (14/7/97)	DAIN (mmol m^{-3})	32.1	1.0	0.6	0.8	0.5	1.5
	DAIP (mmol m^{-3})	7.0	0.4	0.2	0.1	0.2	0.4
	Chlorophyll *a* (mg m^{-3})	9.0	4.1	1.8	2.0	2.2	3.1†
6 (29/7/97)	DAIN (mmol m^{-3})	0.9	11.0	2.0	7.2	0.9	2.6
	DAIP (mmol m^{-3})	0.4	<3.2	0.2	0.1	<0.1	0.1
	Chlorophyll *a* (mg m^{-3})	5.1	1.3	0.4	2.2	3.7	2.5†
6B (11/8/97)	DAIN (mmol m^{-3})	3.8	0.9	0.9	0.9	0.7	1.2
	DAIP (mmol m^{-3})	1.3	0.2	0.3	0.2	0.2	0.4
	Chlorophyll *a* (mg m^{-3})	9.1	9.1	14.6	12.8	21.9	13.5†
7B (27/8/97)	DAIN (mmol m^{-3})	20.6	8.7	1.5	1.5	1.4	3.6
	DAIP (mmol m^{-3})	7.3	4.0	0.9	0.5	0.6	1.5
	Chlorophyll *a* (mg m^{-3})	9.1	16.2	7.9	10.1	9.2	10.5†
7 (9/9/97)	DAIN (mmol m^{-3})	2.2	1.6	0.7	0.8	0.7	1.1
	DAIP (mmol m^{-3})	1.0	3.0	0.7	0.5	0.6	1.5
	Chlorophyll *a* (mg m^{-3})	12.7	6.7	5.6	10.1	9.2	8.4†
8 (30/9/97)	DAIN (mmol m^{-3})	0.8	1.2	1.9	1.1	1.2	1.2
	DAIP (mmol m^{-3})	0.8	0.9	0.8	0.7	0.7	0.8
	Chlorophyll *a* (mg m^{-3})	11.0	11.3	8.5	11.1	60.2	20.4†
8B (14/10/97)	DAIN (mmol m^{-3})	11.4	108.0	4.8	6.6	2.6	10.1
	DAIP (mmol m^{-3})	1.0	13.8	0.4	0.3	0.2	0.8
	Chlorophyll *a* (mg m^{-3})	5.2	2.3	4.5	3.6	2.1	3.5†
9 (29/10/97)	DAIN (mmol m^{-3})	4.3	50.3	60.5	18.2	39.6	24.8
	DAIP (mmol m^{-3})	0.6	5.9	6.2	1.9	3.1	2.6
	Chlorophyll *a* (mg m^{-3})	2.0	3.8	3.0	4.4	3.8	3.4†

† Mean chlorophyll *a* concentrations are expressed as arithmetic mean

4.3 Inputs to the Bay

An earlier CREH report (Stapleton *et al.*, 1997) estimated the proportion of the nutrient input to St. Aubin's Bay from different sources including streams and the sewage treatment plant at Bellozanne. This report indicated that from these sources approximately 50% of the total N budget (i.e. DAIN) and 98% of the P budget (i.e. DAIP) is provided by the STW effluent. The results from the present study allow further budget calculations to be made using a similar methodology. The previous study was unable to include budget calculations for the two La Haule catchments due to the lack of nutrient data.

The percentage contribution of the various inputs to the nutrient budget of St. Aubin's Bay are summarised in Tables 4.5 and 4.6, and in Figures 5.1 and 5.2. Since it was not possible to gain access to the Weighbridge outfall, data from Stapleton *et al.* (1997) is presented in Tables 4.5 and 4.6.

Table 4.5: Estimated contribution of DAIN delivery (%) from catchments and the STW on survey dates.

Survey	St. Aubin's valley	La Haule A	La Haule B	St. Peter's valley	Water works valley	Bello-zanne valley	Weigh-bridge outfall*	All Inputs	STW FE
1 (27/2/97)	7	1	4	18	11	8	30	79	21
2 (2/4/97)	5	1	3	15	7	5	21	57	43
3 (30/4/97)	4	1	2	12	7	6	16	47	53
3B (15/5/97)	4	1	2	11	5	5	17	45	55
4 (3/6/97)	3	0†	1	8	3	3	12	30	70
4B (17/6/97)	3	0†	1	7	4	3	12	30	70
5 (1/7/97)	2	<1	1	5	4	2	8	23	77
5B (14/7/97)	2	0†	1	4	1	2	7	16	84
6 (29/7/97)	2	0†	1	3	3	2	7	17	83
6B (11/8/97)	2	<1	1	2	2	1	7	15	85
7B (27/8/97)	1	0†	1	2	2	1	7	15	85
7 (9/9/97)	2	0†	1	0†	2	2	6	13	87
8 (30/9/97)	<1	0†	<1	<1	<1	1	2	3	97
8B (14/10/97)	3	0†	2	8	5	4	16	37	63
9 (29/10/97)	1	0†	1	4	3	3	12	25	75
Total Load 27/2/97-29/10/97	3	<1	2	7	4	3	12	31	69

* data for the Weighbridge outfall is taken from Stapleton *et al.* (1996)
† no flow

The contribution of Bellozanne treatment plant to the DAIN load entering St. Aubin's Bay increases from a minimum of 21% at the end of February to a maximum of 97% by mid September (Table 4.5 and Figure 5.1a). Whilst the absolute DAIN load from the STW remains relatively stable, varying between $2.8x10^7$ and $5.5x10^7$ mmol per day, the DAIN load from land runoff decreases from

$1.2x10^8$ to $8.3x10^6$ mmol per day (Figure 5.1b). Thus, as the load from the catchments decreases, the relative contribution of the STW increases. The decrease in the catchment DAIN output forms part of a natural cycle with high loads input during the winter and low loads during the summer, primarily as a result of the seasonal variation in nitrate N concentration of stream waters (Stapleton *et al.*, 1997). During the entire study period the STW accounted for 69% of the total DAIN load entering St. Aubin's Bay (Table 4.5). The relative contributions of the individual catchments to the DAIN load during each survey are shown in Figure 5.1c. The greatest DAIN loads are provided by the Weighbridge outfall. Of the outfalls for which data are available, St. Peter's Valley provides the largest DAIN load followed by Waterworks Valley and Bellozanne Valley. Loads of DAIN from the two La Haule catchments (A and B) are generally low, accounting for a maximum of 1% and 4% of the total load respectively.

Table 4.6: Estimated contribution of DAIP delivery (%) from catchments and the STW on survey dates.

Survey	St. Aubin's valley	La Haule A	La Haule B	St. Peter's valley	Water works valley	Bello-zanne valley	Weigh-bridge outfall*	All Inputs	STW FE
1 (27/2/97)	0.3	0.1	5.5	0.7	0.5	0.2	<0.1	7.2	92.8
2 (2/4/97)	0.1	<0.1	0.1	0.3	<0.1	0.1	<0.1	0.6	99.4
3 (30/4/97)	2.0	0.3	1.5	7.1	1.8	1.4	0.1	14.4	85.6
3B (15/5/97)	<0.1	<0.1	0.1	0.7	0.1	<0.1	<0.1	1.0	99.0
4 (3/6/97)	0.1	0†	<0.1	0.3	0.1	<0.1	<0.1	0.5	99.5
4B (17/6/97)	0.1	0†	0.1	0.3	0.1	<0.1	<0.1	0.6	99.4
5B (14/7/97)	0.1	0†	<0.1	0.2	0.3	<0.1	<0.1	0.6	99.4
6 (29/7/97)	<0.1	0†	<0.1	0.2	0.3	<0.1	<0.1	0.6	99.4
6B (11/8/97)	0.1	<0.1	<0.1	0.4	0.2	<0.1	0.1	0.8	99.2
7B (27/8/97)	0.1	0†	<0.1	0.3	0.1	0.1	<0.1	0.6	99.4
7 (9/9/97)	0.1	0†	<0.1	<0.1	0.3	<0.1	<0.1	0.4	99.6
8 (30/9/97)	0.1	0†	<0.1	0.4	0.2	<0.1	0.1	0.9	99.1
8B (14/10/97)	0.1	0†	0.1	0.7	0.3	<0.1	0.4	1.5	98.5
9 (29/10/97)	0.1	0†	0.1	0.5	0.1	<0.1	0.3	1.0	99.0
Total Load 27/2/97-29/10/97	0.1	<0.1	0.7	0.4	0.2	0.1	0.2	1.7	98.3

* data for the Weighbridge outfall is taken from Stapleton *et al.* (1996)

† no flow

N.B. it was not possible to estimate the DAIP delivery during survey 5 (1/7/97) due to DAIP results being provided as "less than" figures.

The DAIP load entering St. Aubin's Bay is clearly dominated by the effluent from Bellozanne STW, which accounts for between 85.6% and 99.6% of the total budget (Table 4.6 and Figure 5.2a). Generally, the absolute DAIP load from the STW varies between $5.2x10^6$ and $8.6x10^6$ mmol per day, although the load is lower during surveys 3 and 3B ($3.2x10^5$ and $2.6x10^6$ mmol per day respectively) (Figure 5.2b). The relative contributions of the individual catchments to the DAIP load during each survey are shown in Figure 5.2c. During the study period, the STW accounted for 98.3% of the total DAIP load entering St. Aubin's Bay. In contrast to DAIN, DAIP loads from the Weighbridge outfall are very low. St. Peter's Valley and Waterworks Valley provide the largest DAIP loads although they both account for less than 1% of the total load. The increased relative importance of the catchment sources during survey 3 is illustrated in Figure 5.2c, with St. Peter's Valley accounting for 7% of the total load. The other exception is a very high load from La Haule B catchment during survey 1 (5.5%). These results are in broad agreement with Stapleton *et al.* (1997).

5. Prediction of trophic state

5.1 Steady state nutrient concentrations

In order to facilitate a comparison between the observed and predicted nutrient and chlorophyll *a* concentrations within St. Aubin's Bay, it is necessary to calculate the potential steady state nutrient and phytoplanktonic biomass concentrations. The UK agreed approach is outlined in CSTT (1994) and this has been followed here.

The potential steady state nutrient concentrations (DAIN and DAIP) can be estimated using:

$$S = S_o + ((s_i + s_d) / (E.V)) \quad \text{mmol m}^{-3} \qquad \textbf{(5.1)}$$

where

- S is the predicted steady state nutrient concentration
- S_o is the nutrient concentration in zone C (mmol m^{-3})
- s_i is the total of local inputs from sources other than the discharge under consideration (mmol d^{-1})
- s_d is the nutrient input from the discharge under consideration (mmol d^{-1})
- E is the relative exchange rate
- V is the volume of the area into which the discharge is made.

CSTT (1994) suggest that the calculation should be carried out for conditions in late winter (with S_o measured in February before the spring phytoplankton bloom has depleted nutrients) and in mid-summer (July to August) for both the present and future values of s_d. However, the exact dates of these conditions will vary between years and with latitude. Therefore, the above equations, and those to determine the maximum biomass of phytoplankton that can be supported by nutrient enrichment, have been solved using the data from each monthly survey.

The relative exchange rate for the bay has been calculated using computer-based hydrodynamic models. For the purposes of solving the CSTT equations a neap tide exchange rate (E) of 0.599 d^{-1} is used and represents a conservative exchange rate. The total nutrient inputs from the discharges were calculated by applying the daily flow rate for the relevant month extracted from Stapleton *et al.* (1997) to the nutrient concentrations of the outfalls collected under this survey. The volume of St. Aubin's Bay was estimated using Admiralty Chart No. 1137 for mid-tide level. The potential steady state nutrient concentrations (S) for DAIN and DAIP, using data from all the full sea surveys described in this report, are shown in Table 5.1.

To investigate the impact of nutrient removal at the Bellozanne plant the above calculations were repeated, replacing the observed DAIN and DAIP concentrations in the STW final effluent with the proposed design criteria; 10 mg l^{-1} DAIN and 1 mg l^{-1} DAIP. The results of these calculations, together with the percentage reduction in S following improved treatment, are shown in Table 5.1 and Figure 5.3. Following presentation of the draft report at a meeting with PSD staff on 14/10/97, further analysis was carried out for proposed DAIN concentrations in the effluent of between 1 mg l^{-1} and 15 mg l^{-1}. This analysis is presented in Appendix VI.

Table 5.1: Predicted steady state nutrient concentrations (S) for DAIN and DAIP for surveys 1 to 8 and predicted concentrations following nutrient removal from the Bellozanne final effluent.

Survey	Nutrient	S (mmol m^{-3}) Observed Data	S (mmol m^{-3}) Proposed Conc.	% decrease in S
1 (27/2/97)	DAIN	15.55	15.14	2.62
	DAIP	0.70	0.48	31.73
2 (2/4/97)	DAIN	14.53	14.06	3.21
	DAIP	0.52	0.36	30.76
3 (30/4/97)	DAIN	4.77	3.72	21.99
	DAIP	0.13	0.14	0†
4 (3/6/97)	DAIN	2.49	1.83	26.56
	DAIP	0.26	0.12	54.55
5 (1/7/97)	DAIN	2.54	1.98	22.15
	DAIP	0.31	0.17	43.19
6 (29/7/97)	DAIN	3.46	2.71	21.71
	DAIP	0.25	0.09	65.09
7 (9/9/97)	DAIN	4.23	3.12	26.30
	DAIP	0.57	0.38	32.68
8 (30/9/97)	DAIN	9.46	3.10	67.20
	DAIP	0.59	0.40	32.90
9 (29/10/97)	DAIN	6.95	5.88	15.38
	DAIP	0.63	0.47	25.15

† the predicted steady state nutrient concentration using observed STW final effluent data was less than that predicted using the proposed concentrations

The predicted mid-tide steady state DAIN concentrations (S_{DAIN}) for observed STW final effluent concentrations (Figure 5.3a) display a similar pattern to the observed geometric mean DAIN concentrations. However, S_{DAIN} during survey 8 (end of September) is considerably greater than the observed concentration (9.5 mmol m^{-3} and 1.8 mmol m^{-3} respectively). This deviation can be attributed to the much higher DAIN concentration in the STW final effluent during survey 8. S_{DAIN} exceeds the CSTT 12 mmol m^{-3} threshold during the first two sea surveys (end of February and beginning of April), although by survey 3 (end of April) S_{DAIN} had fallen below the CSTT threshold. S_{DAIN} remains below this threshold during surveys 4 to 9. Allowing for the relatively constant difference between observed and predicted concentrations, the observed increase in zone B concentrations during survey 9 is predicted.

Predicted mid-tide steady state DAIP concentrations (S_{DAIP}) using the observed effluent concentrations (Figure 5.3b) are all greater than the CSTT DAIP threshold of 0.2 mmol m^{-3}, with the exception of survey 3 (end of April), when $S_{DAIP} = 0.13$. This low S_{DAIP} concentration is primarily a function of the extremely low DAIP concentration observed in the STW effluent during survey 3.

These results suggest that St. Aubin's Bay can be regarded as being **potentially** hypernutrified between the end of February and the beginning of April (i.e. S_{DAIN} is greater than 12 mmol m^{-3} and S_{DAIP} is greater than 0.2 mmol m^{-3}), reflecting the results from the sea surveys. However, both predicted concentrations (i.e. S_{DAIN} and S_{DAIP}) are greater than the geometric mean DAIN and DAIP concentrations observed for each corresponding survey (Figures 5.3a and b), with the exception of the DAIP concentration during survey 2. This suggests that the bay did not exhibit the full impact of nutrient inputs during the period of survey. This may be due to a combination of environmental factors including utilisation of nutrients by phytoplankton and/or a greater water exchange rate than the 'conservative', estimate of a neap tide minimum used in the calculations.

Clearly, improved nutrient removal from the STW effluent stream results in decreased predicted (i.e. S) concentrations for both DAIN and DAIP (the exception is survey 3 when DAIP concentrations in the effluent were extremely low), although the degree of this reduction at the plant varies throughout the period of the study (Table 5.1 and Figure 5.4). The high DAIN concentrations in zone C waters during surveys 1 and 2 are reflected in the relatively small percentage reduction in S_{DAIN} following nutrient removal (2.6-3.2%). A greater reduction of S_{DAIN} was evident after zone C concentrations fell to below the CSTT winter threshold at the end of April, when the percentage reduction increases to 22%. Between this date and mid-September the percentage reduction of S_{DAIN} varies between 22% and 27%. At the end of September, the percentage reduction increases to 67%, although this can be attributed to the high nutrient concentrations observed in the Bellozanne final effluent. The percentage reduction in S_{DAIN} during survey 9 was lower than all surveys since the end of April (survey 3) at 15.4%. This, again, may be a function of the high zone C DAIN concentrations.

The impact of P removal on S_{DAIP} concentrations is more dramatic, removing a minimum of 30% at the end of February (survey 1) and a maximum of 65% during survey 6. Again, the higher DAIP concentrations in zone C during surveys 1 and 2 and again during survey 7 (mid September) are reflected in lower reduction rates. The higher reduction rates resulting from P removal can primarily be attributed to the fact that the Bellozanne STW effluent contributes 98% of the P load into St. Aubin's Bay whilst contributing 50% of the N load (Section 4.3 and Stapleton *et al.*, 1997). P removal would result in S_{DAIP} falling to below the CSTT threshold of 0.2 mmol m^{-3} between surveys 3 and 6, although during the other surveys concentrations remain above this limit.

5.2 Maximum biomass of phytoplankton

The maximum biomass of phytoplankton can be predicted for conditions during each month using the equation:

$$X_{max} = X_o + q.S \text{ mg chl m}^{-3} \qquad \textbf{(5.2)}$$

where

X_{max}	is the maximum biomass chlorophyll concentration
X_o	is the concentration of phytoplankton chlorophyll in zone C
q	is the yield of phytoplankton from nutrient, 1.1 to 2.8 mg chl (mmol DAIN)$^{-1}$, 50 to 100 mg chl (mmol DAIP)$^{-1}$.

Utilising the two figures quoted by CSTT (1994) for phytoplankton yield (i.e. q) as a minimum and maximum, X_{max} can be indicated as a range. Again, this has been calculated using data from all the sea surveys and the results are shown in Table 5.2. X_{max} can also be estimated using both S_{DAIN} and S_{DAIP} for current and proposed treatment scenarios.

The range of DAIN X_{max} and DAIP X_{max} (i.e. the minimum and maximum concentrations defined by the calculation of this parameter), using observed effluent data, are greater than the corresponding mean concentrations observed in zones B and C during all surveys, suggesting actual growth is not occurring at its maximum. Potential DAIN X_{max} concentrations are greater than the CSTT summer X_{max} maximum concentration of 10 mg chl m^{-3} during surveys 1 to 3 (end of February to end of April) and again during surveys 6 to 8 (end of July to end of September) (Table 5.2). DAIP X_{max} concentrations are greater than the CSTT summer X_{max} maximum during all surveys. Comparison of the increase in biomass (i.e. q.S) shows that during all surveys DAIN is the limiting factor for growth since q.S for DAIN is smaller (the exception to this is for the maximum of the range of X_{max} during survey 3 (30/4/97) when DAIP is the limiting factor; however, q.S for DAIN and DAIP are very similar, suggesting the system is approximating equilibrium). This is to be expected since DAIN is the usual limiting factor in marine conditions (CSTT, 1994).

Table 5.2: Estimated range of maximum biomass chlorophyll concentration (X_{max}) for DAIN and DAIP calculated using data from surveys 1 to 8 and proposed concentrations in the Bellozanne final effluent following nutrient removal.

Survey	Nutrient	X_{max} (mg chl m^{-3}) Observed Data	X_{max} (mg chl m^{-3}) Proposed Conc.	% decrease in X_{max}¶
1 (27/2/97)	DAIN	19.3-45.8	18.9-44.6	2.4
	DAIP	37.2-72.1	26.1-49.9	30.3
2 (2/4/97)	DAIN	17.1-41.8	16.6-40.5	3.1
	DAIP	26.9-52.7	19.0-36.8	29.8
3 (30/4/97)	DAIN	7.7-15.8	6.6-12.9	16.7
	DAIP	9.0-15.5	9.5-16.4	0†
4 (3/6/97)	DAIN	3.9-8.2	3.2-6.3	20.6
	DAIP	14.4-27.7	7.2-13.2	51.1
5 (1/7/97)	DAIN	3.8-8.2	3.2-6.6	17.7
	DAIP	16.4-31.7	9.8-18.5	41.1
6 (29/7/97)	DAIN	5.1-10.9	4.2-8.8	17.8
	DAIP	14.0-26.7	5.7-10.1	60.6
7 (9/9/97)	DAIN	6.7-13.9	5.5-10.8	20.3
	DAIP	30.4-58.7	21.1-40.2	31.0
8 (30/9/97)	DAIN	12.2 - 28.2	5.2 - 10.4	60.2
	DAIP	31.2-60.7	21.5-41.3	41.3
9 (29/10/97)	DAIN	9.1-20.9	8.0-18.0	13.6
	DAIP	32.8-64.1	24.9-48.4	24.3

† the predicted maximum biomass chlorophyll concentrations using observed STW final effluent data were less than that predicted using the proposed concentrations
¶ mean % reduction between minimum and maximum of range

Results of calculations based on proposed nutrient removal scenarios are shown in Table 5.2 The mean percentage reduction of X_{max} (Table 5.2) displays a similar distribution to the percentage decrease in S_{DAIN} and S_{DAIP}; this is unsurprising given that X_{max} is a function of S. DAIP X_{max} displays a greater percentage reduction due to the fact that the final effluent provides up to 99% of the total DAIP load as opposed to only 50% of the DAIN load (Section 4.2). Again, the high concentration of DAIN in the final effluent from Bellozanne STW during survey 8 is reflected in a greater percentage reduction when nutrient removal is applied. The reduction of nutrients in the effluent stream, whilst resulting in reduced DAIN X_{max} and DAIP

X_{max}, shifts the range of DAIN X_{max} to below the CSTT summer threshold during survey 6 (29/7/97).

Further analysis was carried out to determine the impact on X_{max} of proposed DAIN concentrations in the Bellozanne effluent of between 1 mg l^{-1} and 15 mg l^{-1}. This is presented in Appendix VI.

5.3 Relative rate of light controlled growth

To establish whether circumstances are suitable for phytoplankton growth, the relative rate of light controlled growth can be calculated using the equation (CSTT, 1994):

$$\mu = \alpha(m_2 . I_o / (\lambda.h) - I_c)\ d^{-1} \qquad \textbf{(5.3)}$$

where

μ	is the relative rate of light controlled growth;
α	is a photosynthetic efficiency with a spring value of 0.030 and a summer value of 0.015 d^{-1} $(\mu E\ m^{-2}\ s^{-1})^{-1}$;
m_2	= 0.37, allows for extra attenuation of polychromatic photosynthetically available radiation (PAR) near the sea surface;
I_o	is the 24-hour mean sea-surface PAR;
λ	is the diffuse attenuation coefficient for most downwelling PAR.
h	is the mean depth of the defined volume;
I_c	= 12μE m^{-2} s^{-1}, is the compensation irradiance, the minimum allowing phytoplankton growth.

In the absence of suitable data to solve the equation for the relative rate of light controlled growth[6], values for I_o, λ and I_c given by CSTT (1994) for the outer section of Milford Haven are used. The mean depth of St. Aubin's bay at mid-tide (7.45m) has been used to represent h.

The potential maximum biomass will be realised only if the relative rate of light controlled growth is greater than the sum of the exchange rate of water and the rate of loss of phytoplankton through grazing by zooplankton and benthic filter feeders: i.e.;

$$\mu > (E + L) \qquad \textbf{(5.4)}$$

where

L	is the relative loss rate of phytoplankton by zooplankton and benthic filter feeders. A conservative approach is to take L = 0.0 d^{-1} (i.e. zero loss of phytoplankton);
E	is the relative exchange rate.

Table 5.3 summarises the relative rates of light controlled growth (μ) calculated for March (average sun) and June (average and full sun) together with an assessment of the results.

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[6] Attempts were made to measure the diffuse attenuation coefficient (λ) using a Skye Instruments quantum sensor. However, the effects of wave action on light diffraction through the water column resulted in fluctuations of over two orders of magnitude within a very short timescale.

The results presented in Table 5.3 indicate maximum biomass may be realised during neap tides in March and during both spring and neap tides in June. This implies that conditions within St. Aubin's Bay gradually become suitable for maximum chlorophyll biomass development: first intermittently, during neap tides; gradually extending over time to encompass wider tidal ranges; finally extending over the whole spring-neap cycle by the beginning of June.

Table 5.3: Results of calculations to estimate the potential for maximum phytoplankton biomass.

	μ (d^{-1})*	(E + L)†	Result
March (average sun)			
Neap tides	0.65	0.6 + 0.0 = 0.6	μ > (E + L)
Spring Tides		0.7 + 0.0 = 0.7	μ < (E + L)
June (average sun)			
Neap tides	0.95	0.6 + 0.0 = 0.6	μ > (E + L)
Spring Tides		0.7 + 0.0 = 0.7	μ > (E + L)
June (full sun)			
Neap tides	1.40	0.6 + 0.0 = 0.6	μ > (E + L)
Spring Tides		0.7 + 0.0 = 0.7	μ > (E + L)

* μ = relative rate of light controlled growth

† (E + L) = relative exchange rate + relative loss rate of phytoplankton by zooplankton and benthic filter feeders

6. Discussion

To determine whether it is necessary to install nutrient removal at the Bellozanne plant under the terms of the UWWTD three key questions need to be addressed:

- Are the waters into which the discharge is made (i.e. St. Aubin's Bay) a Sensitive Area?
- Does the current treatment works comply with nutrient standards laid down in the Directive?
- Will additional treatment have an affect on eutrophication?

A Sensitive Area is defined in the UWWTD as a river, estuary or coastal water which is eutrophic or displays the potential to become eutrophic.

A coastal water is not adversely affected by a discharge if, for zone B:

i) there are no observations showing summer DAIN > 12 mmol m^{-3} (in the presence of at least 0.2 mmol m^{-3} DAIP), nor does equation 5.1 predict such concentrations: that is , there is no evidence, or likelihood, of hypernutrification;

or, if, when hypernutrification has been demonstrated or predicted,

ii) there are no observations showing summer chlorophyll *a* >10 mg m^{-3}, nor does equations 5.2 and 5.3 predict such concentrations when conditions allow phytoplankton growth to exceed losses: that is, there is no evidence, or likelihood, of eutrophication;

or if, eutrophication has been demonstrated or predicted,

iii) the application of secondary treatment[7] will reduce the predicted maximum chlorophyll by less than 1 mg m^{-3}.

Thus, the assessment of St. Aubin's Bay requires both observed and predicted data. Table 6.1 summarises the assessment of points (i) to (iii), which has been completed using zone B and nearshore data.

6.1 Hypernutrification

The geometric mean DAIN concentrations in zones B and C, together with the geometric mean of the nearshore samples, were found to exceed the CSTT (1994) 12 mmol m^{-3} threshold between the end of February and the beginning of April. Thereafter, DAIN concentrations have remained relatively low and below the threshold, although an increase in concentrations was observed during the final survey which may be related to the reduced uptake by phytoplankton as ideal growing conditions diminish. Generally, concentrations in the immediate nearshore zone also remained below the threshold until the final survey, when the geometric mean concentration exceeded 12 mmol m^{-3}. DAIP concentrations in zones B and C exceeded the 0.2 mmol m^{-3} threshold between the end of February and the beginning of April and again after mid-September. However, in the nearshore zone, DAIP concentrations, generally, exceeded the threshold throughout the study period. Thus, winter hypernutrification is indicated at the beginning of the study period, although it is not present during the summer. The final survey indicated an increase in nutrient concentrations which may be expected as phytoplankton growth is inhibited as winter approaches, although hypernutrified conditions are not reached.

Table 6.1: Assessment of the effects of the Bellozanne discharge on zone B and the nearshore zone based on CSTT criteria. (refer to text for details)

	Zone B	Nearshore zone
Paragraph (i) (Section 6.1)		
Observed summer DAIN>12 $mmol^{-3}$ and DAIP>0.2 $mmol^{-3}$?	✗	✗
Predicted S_{DAIN}>12 $mmol^{-3}$ and S_{DAIP}>0.2 $mmol^{-3}$?	✗	✗
Paragraph (ii) (Section 6.2)		
Observed summer chlorophyll *a* > 10 mg m^{-3} ?	✗	✓
Predicted summer X_{max} > 10 mg m^{-3} ?	✓	n/a
Paragraph (iii) (Section 6.3)		
Nutrient removal reduces summer X_{max} > 1 mg m^{-3}	✓	n/a

6.2 Eutrophication

A region is potentially eutrophic if:

- observed chlorophyll concentrations regularly exceed 10 mg m^{-3} during summer;

[7] In the current situation, this will be assumed to mean nutrient removal.

- the relative rate of light-controlled phytoplankton growth (μ) is greater than the reactive water exchange rate (E) plus the relative loss rate of phytoplankton by grazing (L) (i.e. $\mu > E+L$) and the predicted summer maximum chlorophyll concentration (i.e. X_{max}) is greater than 10 mg m^{-3}.

Observed chlorophyll *a* concentrations in zone B at no time exceeded 10 mg m^{-3} (Table 4.1). However, the samples collected from the immediate nearshore zone (i.e. B1-B5) (Section 4.2) have means in excess of 10 mg m^{-3} during August and again at the end of September.

The predictions in Section 5.3 show the relative rate of light-controlled phytoplankton growth is greater than the water exchange rate plus the relative loss of phytoplankton by grazing during neap tides in March, and during all tidal states in June (Table 5.3). The predicted summer maximum chlorophyll concentration (using S_{DAIN}, the limiting nutrient for phytoplankton growth) in zone B exceeds 10 mg chl m^{-3} between the end of July and the end of September.

Thus, in zone B eutrophication is not observed although potential eutrophication is indicated by predicted chlorophyll concentrations. However, eutrophic conditions are observed in the immediate nearshore zone.

6.3 Impact of nutrient removal from effluent

The proposed nutrient removal from the Bellozanne effluent results in a decrease in predicted maximum chlorophyll biomass of between 0.4 and 3.1 mg chl m^{-3} for DAIN X_{max} and between 6.6 and 22.2 mg chl m^{-3} for DAIP X_{max} (Table 6.2). The range of predicted reductions in DAIN X_{max} (the limiting nutrient for growth) exceeds the required 1 mg chl m^{-3} reduction described in (iii) above, suggesting that the current effluent discharge does have an adverse affect on the environment and nutrient removal is worthy of consideration. A more complete analysis of the impacts of nutrient removal on zone B chlorophyll concentrations is presented in Appendix VI, which considers DAIN concentrations in the effluent of between 1 mg l^{-1} and 15 mg l^{-1}.

Table 6.2: Predicted range of maximum chlorophyll biomass (X_{max}) removal from zone B after applying nutrient removal to the Bellozanne effluent.

Survey	Decrease in predicted maximum chlorophyll biomass (mg chl m^{-3})	
	DAIN X_{max}	DAIP X_{max}
1 (27/2/97)	0.4-1.1	11.1-22.2
2 (2/4/97)	0.5-1.3	7.9-15.9
3 (30/4/97)	1.2-2.9	0†
4 (3/6/97)	0.7-1.9	7.2-14.4
5 (1/7/97)	0.6-1.6	6.6-13.2
6 (29/7/97)	0.8-2.1	8.3-16.6
7 (9/9/97)	1.2-3.1	9.2-18.5
8 (30/9/97)	7.0-17.8	9.7-19.4
9 (29/10/97)	1.2-3.0	7.9-15.7

† the predicted maximum biomass chlorophyll concentrations using observed STW final effluent data were less than that predicted using the proposed concentrations

6.4 The status of St. Aubin's Bay

The above assessment shows that hypernutrification is present only during the winter, with observed and predicted summer DAIN concentrations well below the threshold of hypernutrification. It is not uncommon for hypernutrification to occur during the winter, when algal growth and hence, uptake of available nutrients, is inhibited.

The low summer concentrations of DAIN appear to limit algal growth, with maximum growth predicted to remain below the threshold of eutrophication until the end of July. Thereafter, predicted chlorophyll *a* concentrations were greater than 10 mg m^{-3}, indicating potentially eutrophic conditions. During this period, there is little variation in both the observed background chlorophyll *a* concentrations and the total DAIN load from catchment and STW sources. These are all input parameters for the predictive model for maximum chlorophyll concentration. Hence, minor fluctuations in any combination of these parameters combine to increase the maximum chlorophyll concentration over the threshold for eutrophication. In such circumstances, therefore, the removal of part of the total DAIN load by installing nutrient removal to the Bellozanne final effluent will help to reduce the potential for eutrophication (a 17% to 20% decrease in maximum chlorophyll concentrations is predicted between the end of April and mid-September).

The immediate nearshore zone, which is most likely to be utilised by recreators, appears to be even more sensitive to eutrophication, with observed concentrations of chlorophyll *a* exceeding the threshold in August. Since the PSD outfall does not extend below low water mark, the discharge relies on the high quality of the effluent to achieve compliance with water quality regulations rather than on dilution of the effluent in sea water. Thus, when the outfall is exposed, initial mixing may be limited, particularly on calm days. In such cases, it is possible that a buoyant effluent slick may form in the nearshore zone which experiences only partial mixing. Similarly, the streams which discharge into St. Aubin's Bay, and which contain high N concentrations, may form similar buoyant slicks. This study has clearly shown that both DAIN and DAIP concentrations are elevated within this nearshore zone.

Despite the absence of summer hypernutrification, St. Aubin's Bay appears to be potentially eutrophic in that <u>predicted</u> chlorophyll concentrations exceed 10 mg m^{-3} during the late summer. The lower than predicted DAIN concentrations observed throughout the summer suggest that maximum phytoplankton growth was not achieved during this study period, with the low DAIN concentrations limiting growth. Hence, maintenance of the low DAIN concentrations in zone B will help to prevent eutrophic conditions developing. Table 6.2 has demonstrated that installation of nutrient removal will reduce the predicted maximum chlorophyll concentration by more than 1 mg m^{-3}, a criterion by which CSTT consider an effluent to have an adverse affect on the environment. Given these facts, and the apparent sensitivity of St. Aubin's Bay to potential eutrophication, it is suggested that the precautionary approach is adopted and nutrient removal is installed at Bellozanne.

If St. Aubin's Bay were to be considered a potential 'Sensitive Area', then, discharges to a SA from a plant with a population equivalent similar to that of Bellozanne (100,000pe) should contain a maximum of 10 mg l^{-1} DAIN and 1 mg l^{-1} DAIP. At present the Bellozanne plant does not comply with these criteria. Finally, nutrient removal will reduce the maximum predicted chlorophyll concentration by greater than 1 mg m^{-3}, hence having an affect on potential eutrophication. Under these criteria, nutrient removal should be installed at sites wishing to comply with the UWWTD.

It should be noted that this study and recommendations above are based on data collection from only one summer season. This could be considered anomalous in that the analysis of sunshine hours and sea temperature data (Appendix V) display significant variations from 30 year monthly averages. CSTT (1994) suggest that it would be normal to base expenditure decisions in this area on at least two years data. However, the time constraints necessitated by the decision timescales for infrastructure investment at Bellozanne have not allowed this protracted, but possibly more prudent, data acquisition.

7. Summary

1. The States of Jersey Public Services Department is considering options for upgrading the Bellozanne sewage treatment plant. The design criteria should meet the requirements of current and proposed European Union legislation, in particular, the Urban Waste Water Treatment Directive (91/971/EEC) (UWWTD).

2. The UWWTD requires nutrient removal systems to be installed at treatment plants which discharge into Sensitive Areas (SA). These are waters which are eutrophic, or which, in the near future, may become so if action is not taken.

3. An assessment of nitrogen and phosphorus loads entering St. Aubin's Bay indicated that the Bellozanne treatment plant contributes 50% of the annual total nitrogen load and 98% of the annual total phosphorus load.

4. Two separate surveys have been completed. <u>First</u>, sea surveys of St. Aubin's Bay (i.e. Zone B in the Table below). <u>Second</u>, surveys of the immediate nearshore zone and catchment and sewage effluent inputs to the Bay.

5. Predicted and observed nutrient concentrations within St. Aubin's Bay indicated hypernutrification (i.e. excess nutrient concentration) was present during winter. However, throughout the summer period, dissolved available inorganic nitrogen (DAIN) concentrations were low.

6. Despite predicted chlorophyll concentrations indicating potential eutrophication, chlorophyll *a* concentrations within St. Aubin's Bay (Zone B) were low throughout the survey period. Data from the immediate nearshore surveys indicated eutrophic conditions between mid August and the end of September.

7. Nutrient removal from the Bellozanne effluent was predicted to decrease maximum chlorophyll concentrations in St. Aubin's Bay by more than 1 mg m^{-3}. This represents a decrease of chlorophyll concentrations by 2% - 21% .

8. An assessment of the effects of the Bellozanne discharge on St. Aubin's Bay are summarised in the Table 7.1 below.

9. Despite the absence of hypernutrification during summer, St. Aubin's Bay displays some evidence of eutrophication in the nearshore area and potential for eutrophication in the Bay itself (i.e. zone B). Therefore, nutrient removal from the Bellozanne effluent would be a prudent precautionary step.

10. These recommendations are based on data collection from one summer season. Analysis of sunshine hours data indicated that, in terms of irradiance, this is possibly

anomalous. UK practice would be to base expenditure decisions on at least two years' data where that was available.

Table 7.1: Assessment of the effects of the Bellozanne discharge on zone B and the nearshore zone based on CSTT criteria.

	Zone B	Nearshore zone
Observed summer N and P over recommended level	NO	NO
Predicted summer N and P over recommended level	NO	NO
Observed summer chlorophyll *a* > 10 mg m^{-3} ?	NO	YES
Predicted summer chlorophyll > 10 mg m^{-3} ?	YES	n/a
Nutrient removal reduces summer chlorophyll > 1 mg m^{-3}	YES	n/a

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