CREH

Centre for
Research into
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Ressessment of the trophic status of St Aubin's Bay, Jersey 2009-2010

A Report to
Transport and Technical Services, States of Jersey

[redacted]

November 2010
Final Report

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Executive Summary

1. Thus study provides a reassessment of the trophic status of St. Aubin's Bay, following a similar programme of empirical data collection and model prediction used in the original assessment, carried out in 1997. Both studies were designed to provide data suitable for application of the methodology proposed by the competent authorities of the British Government (CSTT, 1997).

2. In this study, conducted from 1st June 2009 to 1st July 2010, empirical data were collected describing nutrient concentrations in inputs discharging into St. Auburns Bay (streams and Bellozanne STW final effluent (FE)) and in the marine receiving waters. Nutrient flux was quantified in terms of Dissolved Available Inorganic Nitrogen (DAIN), Dissolved Available Inorganic Phosphorus (DAIP) and Dissolved Reactive Silicon (DRS). Chlorophyll *a* provided a measure of phytoplankton biomass.

3. Total nutrient flux into St. Aubin's Bay from streams and the Bellozanne STW FE were very similar to those of 1997 and 2007. In the present study, Bellozanne STW accounted for 72% of the annual DAIN input, although the proportional contribution of the streams varied through the full study, accounting for up to 58% of the flux during the February to April period. The majority of DAIP was delivered from the STW effluent although there was a considerable reduction in load when compared to 1997.

4. The results of the empirical data collection and CSTT modelling implicate DAIN as the limiting nutrient for phytoplankton growth in St. Aubin's Bay, which is typical of marine waters generally.

5. The observed data and CSTT model results (using recommended phytoplankton chlorophyll yield values) indicated that St. Aubin's Bay is not subject to eutrophication. Both observed and predicted nutrient concentrations demonstrated winter hypernutrification (elevated nutrient concentrations) although summer concentrations of chlorophyll *a* were below the relevant threshold. Some elevated chlorophyll *a* concentrations were observed in the immediate nearshore surf-zone although no oxygen depletion or nuisance algal blooms were observed.

6. A more stringent application of the CSTT models, using a 'worst-case' 90-percentile value for phytoplankton chlorophyll *a* yield resulted in predicted chlorophyll *a* concentrations above the 'eutrophic' threshold between March and the end of June. However, CSTT state the threshold should only apply to 'summer' concentrations after the spring bloom. The monthly nature of the offshore surveys makes it difficult to identify the end of the bloom period but, based on observed nutrient and chlorophyll *a* data, sometime between the end of April and beginning of June is suggested. Thus, only the predicted data for the beginning of June might be indicative of potential eutrophication, although the threshold is exceeded by a relatively small amount.

7. A 1 mg m^{-3} decrease in chlorophyll *a* concentrations in St. Aubin's Bay would be predicted, i.e. given a reduction in DAIN concentration in the Bellozanne STW effluent to less than 17.7 mg l^{-1}.

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1. Introduction

As part of the *Liquid Waste Management Strategy* under development for the States of Jersey Transport and Technical Service (TTS), CREH were commissioned to advise on field survey design and undertake data analysis necessary to provide a reassessment of the trophic status of St. Aubin's Bay. A previous study undertaken by CREH for the States of Jersey during 1997 (Stapleton and Kay, 1997, Stapleton et al., 2000) concluded that, through application of the recommended methodology of the Comprehensive Studies Task Team (CSTT, 1994, 1997), installation of nutrient removal technology at Bellozanne STW would be a prudent precautionary step to reduce potential eutrophication in St Aubin's Bay. The report found that, despite predicted chlorophyll *a* concentrations for the bay indicating potential eutrophication, observed concentrations were low throughout the study period, with the occasional exception within the immediate nearshore zone. Winter hypernutrification (elevated nutrient concentrations) was observed within St. Aubin's Bay during the study period, although nutrient levels were low throughout the summer (i.e. phytoplankton growing) season, again with some high concentrations observed within the immediate nearshore, surf, zone. The proposed nutrient concentrations within the Bellozanne treated final effluent after installation of nitrogen removal processes (total nitrogen = 10 mg l^{-1}) were predicted to decrease maximum chlorophyll *a* concentrations by over 1 mg m^{-3}.

This current study was commissioned because nitrogen removal processes installed at Bellozanne wastewater treatment works (STW) have not matched the design criteria. A study into nutrient fluxes into St. Aubin's Bay, undertaken by CREH in 2007 (Wyer *et al.,* 2008), concluded that the overall nitrogen flux to St Aubin's Bay had not changed appreciably between the 1997 and 2007 estimates. The change in total dissolved available inorganic nitrogen (DAIN) load in 2007 only amounted to a 2.3% reduction compared to 1997. Changes in proportional contribution suggested that a 17% reduction of DAIN from streams was offset by a 10% increase in DAIN from the STW effluent. In contrast, dissolved available inorganic phosphorus (DAIP - PO_4-P) loads showed a consistent reduction between 1997 and 2007, reflecting both the significant reduction of DAIP concentrations in the STW effluent and little concentration change in streams during 1997 and 2007.

The current study design utilised the same methodology as the 1997 study i.e. monthly offshore surveys of St. Aubin's Bay and waters further south interlaced with approximately fortnightly surveys of the surface water stream and sewage inputs to St. Aubin's Bay and seawater sampled from the beach, in the nearshore zone. Sampling was undertaken by TTS following a detailed method statement provided by CREH. Dr Carl Stapleton, who managed the field sampling during the 1997 study and provided assistance with the first survey. The National Laboratory Service of the England and Wales Environment Agency (EANLS) was commissioned to undertake the laboratory analysis of the water samples (nutrients and chlorophyll *a*). It was the responsibility of CREH to provide analysis of the empirical field data and to report the findings to TTS.

2. Study design & implementation

2.1 Study Design

The 1997 study was designed to provide an assessment of the trophic status of St. Aubin's Bay and the impact of Bellozanne STW against the requirements of the Urban Waste Water Treatment Directive (UWWTD) 91/271/EEC (Anon, 1991). Briefly, the UWWTD requires nutrient removal systems to be installed at treatment plants that discharge into Sensitive Areas. These are waters that are eutrophic, or have the potential to become eutrophic if action is not taken. In the UK, recommendations for the assessment of waters under the UWWTD were made by CSTT in 1994 (CSTT, 1994) and revised in 1997 (CSTT, 1997). The main difference in the 1997 recommendations is the amendment of the criterion defining hypernutrification which refers to '*no <u>winter</u> hypernutrification*' which is a change from the 1994 wording of '*no <u>summer</u> hypernutrification*' used in the original 1994 edition of the CSTT recommendations (CSTT, 1994). Other changes include additional notes describing which phytoplankton chlorophyll yield value should be used in the models and clarification regarding interpretation of results. The CSTT model calculates the maximum phytoplankton chlorophyll concentration that could occur in summer for a given nutrient loading, where the term 'nutrient' means nitrogen and phosphorus in compounds available to phytoplankton. Eutrophication is indicated when the potential chlorophyll concentrations exceed specified limits during the summer. Waters are considered 'at risk' when the potential for eutrophication exists in summer together with the presence of hypernutrification during the winter. Thus, a full assessment of the trophic status of a body of water can only be completed when both summer and winter conditions have been assessed.

Population of the CSTT model requires:

i nutrient flux data for contributing sources, i.e. the surface water streams and sewage inputs; and

ii empirical nutrient and chlorophyll concentration data from the receiving water, i.e. the sea within St. Aubin's Bay and further offshore.

A detailed field survey manual was provided to TTS describing the proposed sampling programme and field protocols. The sampling programme was designed to collect both water quality data (nutrients, chlorophyll, etc.) and hydrological data (stream level and velocity data for discharge estimates) to augment existing data sources (e.g. rainfall and sewage flow data). The water quality data collection was divided into two elements:

i <u>Beach surveys</u>: Onshore surveys of seawater collected from pre-defined points within St. Aubin's Bay plus samples of the freshwater and effluent inputs discharging into the bay, originally planned to be taken at approximately 2-week intervals (i.e. coinciding with sea surveys and mid-way between the sea surveys). This element provides empirical data both for flux calculation (i.e. the inputs) and to describe the receiving water (i.e. nearshore surf zone); and

ii <u>Sea surveys</u>: Offshore surveys of zones A-C from a suitable sampling vessel, to be taken at approximately monthly intervals. Three 'enhanced' surveys during the height of summer should also include samples taken from different depths to investigate vertical stratification. These surveys provide empirical data to describe the receiving water.

It was recommended that, whenever possible, the sea and beach surveys should be undertaken on the same day.

Field surveys during 1997 were undertaken between 27/02/97 (i.e. first sea survey) and 29/10/97 (i.e. final sea survey). This resulted in 9 sea surveys with beach surveys undertaken mostly on the same day, plus a further 6 beach surveys undertaken between the sea surveys starting on 15/05/97. The results from these surveys are presented in detail in Stapleton and Kay (1997) and Stapleton et al. (2000).

Field surveys for the reassessment were started on 01/6/09 (i.e. mid-way through a typical phytoplankton growing season) with the intention of collecting for a full growing season by continuing surveys into 2010 and including the late-winter and spring phytoplankton bloom period, thus, to acquire data necessary for a full assessment under the CSTT (1997) criteria. Whilst the intention was to undertake monthly offshore surveys, vessel availability and inclement weather resulted in only three of the six planned surveys being completed during 2009 (Offshore surveys 1 – 3; Table 2.1). A further five offshore surveys were carried out during the period March to June 2010 (Offshore surveys 5 – 9; Table 2.1). Three 'enhanced' offshore surveys were planned to include collection of samples from three depths (one-third depth, two-thirds depth and sea bed), in addition to surface samples, plus measurement of physico-chemical parameters using a depth-profiling sonde. One such survey was partially completed in which no depth sonde was available for profiling (Offshore survey 4; Table 2.1). In this survey water quality samples were collected from the sea surface and at depth from the profile sample points. The final two surveys (Offshore 8 and 9) include collection of samples from below the sea surface as well as the deployment of a depth sonde for vertical profiling. A total of twelve beach surveys were carried out at approximately fortnightly intervals between 01/06/09 and 27/10/09, with a further ten carried out between 08/02/10 and 01/07/10 (Table 2.1).

2.2 Nutrient flux estimation

Nutrient flux estimates, l, for each input source, s, require two components:

i nutrient concentration, C; and

ii discharge volume V;

expressed in compatible units (e.g. C as kg/m^3 and V as m^3). The flux (e.g. kg) is then calculated as:

$$l_s = C_s \times V_s, \qquad 1$$

with the total flux, L, for all k sources given by:

$$L = \sum_1^k l_s \qquad 2$$

The sampling and measurement programme of the stream and sewage inputs discharging into St. Aubin's Bay was implemented to facilitate calculation of these quantities during 2009 and 2010.

2.3 Hydrology

2.3.1 Stream level

Staff gauges were previously installed at suitable locations on the brooks draining to St Aubin's Bay during the 2007 study (Wyer et al, 2008). At locations used for discharge measurement (Figure 2.1), pressure transducers were installed (Van Essen Instruments "Divers") at the staff gauge sites. These were set to record stream levels (m) continuously at 15-minute intervals. Additional "Divers" were installed in the open atmosphere close to the discharge gauging sites in the St Brelade's stream catchment (site 101a) and Grands Vaux (site 107b). These atmospheric units were used to correct, or compensate, the stream level records with respect to prevailing atmospheric pressure.

The resulting stream level records were then related to staff gauge readings (m) taken during sampling runs and discharge gauging. This provided a continuous sequence of stream level measurements, which were then converted to discharge values as outlined below. Level records were available for two six-month periods, (i) from 1st June to 25th November 2009 and (ii) from 2nd February to 8th July 2010.

2.3.2 Discharge

Discharge measurement procedures followed the England and Wales Environment Agency Hydrometric manual (EA, 2003). This involved measuring water velocity, v (m/s), at regular vertical intervals, b_n (m), across a stream cross-section at 0.6 of the depth, d_n (m), from the water surface. This velocity, $v_{0.6}$, is recognised as a reliable estimate of the average velocity through each vertical in the cross-section. Velocities were measured using an electro-magnetic velocity meter (Valeport Model 801). Three measurements were recorded at each point across the profile and the velocity, $v_{0.6n}$, calculated as the average of these. Velocity was considered to be zero at the extremities (i.e. stream banks) of the cross-section. The discharge, q_i (m^3/s), for each segment, i, of the cross-section was then calculated using the mean section method (Figure 2.2):

$$q_i = (b_{n+1} - b_n) \times (\frac{d_{n+1} + d_n}{2}) \times (\frac{v_{0.6n+1} + v_{0.6n}}{2}) \qquad 3$$

and the total discharge, Q (m^3/s), for the gauging calculated by summing the values for all k segments:

$$Q = \sum_{1}^{k} q_i . \qquad 4$$

Discharge rating curves, relating stream level staff gauge, or stage, readings to discharge were then generated by exploring the relationships between stage, h (m), and discharge. These generally follow a power function form:

$$Q = m \times h^a \qquad 5$$

although linear functions were also considered:

$$Q = m \times h + a \qquad 6$$

where m and a are constants derived from regression analysis (see Section 2.5). The discharge results were processed to produce sequences of average hourly level.

Discharge estimates for STW effluent were based on operational records of flow to the plant (FTP) and flow to full treatment (FFT). These were recorded on a daily basis at 06:30 am. The difference between FTP and FFT yields the daily storm flow through the works, which is partially treated.

2.3.3 Rainfall

Rainfall records (mm) were available for gauges at the STW and at two Jersey Meteorological Department stations, at the Airport and Maison St Louis Observatory (Figure 2.1). Hourly records for the latter two sites were used to generate daily totals to match the 06:30 am daily readings for the Bellozanne gauge.

2.3.4 Drainage basins

The drainage basin boundaries used in the current study were those generated during the 2007 source apportionment study (Wyer et al., 2008). These were derived using a 10 m digital elevation model (DEM) of the island using geographical information system routines available in the Geographical Resources Analysis Support System (GRASS, version 6.0) (Neteler and Mitasova, 2008). Boundaries were generated for each sampling site, each discharge gauging site and for reservoir outlet sites in St Peter's Valley, Waterworks Valley and Grands Vaux (Figure 2.1). Drainage basin areas were used to estimate discharge for un-gauged catchments (e.g. La Haule A and B, Waterworks Valley and Bellozanne Valley). Catchment areas were also used to scale discharge estimates from inland discharge gauging sites to sampling sites at the coast (e.g. sites 101, 104 and the lower portion of the catchment draining to site 107, downstream of the discharge gauges at sites 107a and 107b).

2.4 Surface water stream and effluent sampling and analysis

2.4.1 Inputs to St Aubin's Bay

Direct inputs to St Aubin's Bay include seven brooks and the effluent from Bellozanne STW, as defined in previous studies (Figure 2.1). All brooks between the St Brelade's stream at St Aubin's harbour (site 101, Figure 2.1) and Waterworks Valley (site 105, Figure 2.1) were sampled at the coast. The stream draining Bellozanne valley was sampled at the STW (site 106, Figure 2.1) as it combines with the effluent down stream of this site. Access to the "Town Brook" was provided via an access chamber near the St Helier marina (site 107, Figure 2.1). This stream, which discharges via the Weighbridge outfall, is potentially the largest surface water input to the bay.

The effluent from the Bellozanne STW, combined with the stream draining the Bellozanne Valley, was sampled either at the end of the outfall (site 301, Figure 2.1) (low water) or at the First Tower pumping station (site 301b, Figure 2.1) (high tidal states). Table 2.2 provides details of sampling site locations. Additional final effluent samples were collected at the Bellozanne STW site.

All sites were sampled at approximately biweekly intervals during the two six month monitoring periods (June-November 2009, February-July 2010; Table 2.1).

2.4.2 Offshore sampling in St Aubin's Bay

To determine the potential effect of a discharge to coastal waters CSTT (1997) 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 (Figure 2.3). Samples from zone C were collected from the same locations defined during the 1997 survey (Figure 2.4). Samples within zone B were collected from a series of points along three transects, again, replicating the sampling strategy from the 1997 surveys. The central transect extended between the Ruaudière Buoy and the end of the Bellozanne outfall with one flanking transect either side of the central transect (Figure 2.4). The specific sample points were defined during the first 2009 offshore survey and GPS-derived co-ordinates retained for repeat visits during subsequent surveys.

To provide further data describing the receiving water five additional sample transects were identified for the collection of samples from within the surf zone (Figure 2.3), accessed by wading from the beach. These data were not intended as part of the parameterisation data set for the CSTT model, rather included to provide an indication of concentrations in the initial mixing zone of the terrestrial inputs and the area most likely to be used by beach recreators.

A displacement water sampler was used to collect offshore water samples (i.e. in zones B and C) from specified depths (one third-depth, two third-depth and sea bed) calculated from the depth provided by the survey vessel echo-sounder on arrival at the sample point. A YSI Inc. (Ohio, USA) 6600 V2 multiparameter water quality sonde was used to measure vertical profiles of temperature (˚C), dissolved oxygen (% saturation and mg

l^{-1}), conductivity (µS cm), salinity (ppt) and turbidity (NTU). The sonde included a depth sensor to log readings at 1m intervals through the water column.

2.4.3 Sample analysis

Water samples were tested *in-situ* for temperature (˚C), dissolved oxygen (% saturation and mgl^{-1}) and electrical conductivity (µS)/total dissolved solids (TDS, mgl^{-1})/salinity (ppt) using WTW Oxi 3310 and Cond 3310 meters. Samples intended for nutrient analysis were filtered through 45µm disposable filters in the field and immediately placed in light-proof cool boxes for transport. Unfiltered seawater was collected into 1 litre green PET bottles for chlorophyll *a* analysis and the samples were again placed into light-proof cool boxes for transport. The filtered nutrient and chlorophyll *a* samples were dispatched as soon as possible after the survey to the NAMAS accredited EANLS laboratory in Starcross, Exeter, for analysis.

Filtered samples were analysed for three forms of inorganic nitrogen (N): ammoniacal-N (NH_3-N), nitrite-N (NO_2-N) and nitrate-N (NO_3-N) as well as phosphate-phosphorus (PO_4-P) and dissolved reactive silicon (DRS) (mgl^{-1}) using segmented flow analysis based on methods set out by the Standing Committee of Analysts Methods for the Examination of Waters and Associated Materials (MEWAM). Unfiltered samples were analysed for chlorophyll *a* content (μgl^{-1}) using spectrophotometric filtration and acetone extraction. Concentration values were converted to units suitable for CSTT assessments, namely mmol m^{-3} for nutrients and silicon and mg m^{-3} for chlorophyll *a*.

The concentration of dissolved available inorganic nitrogen (DAIN) in a sample was calculated as:

$$DAIN = NH_3\text{-}N + NO_2\text{-}N + NO_3\text{-}N \qquad 7$$

PO_4-P represents the dissolved available inorganic phosphorus concentration, DAIP.

2.4.4 Additional data

Further nutrient concentration data were available for the STW final effluent during the study periods. These derive from the routine operational records at Bellozanne STW, from samples collected, typically, at least twice weekly.

2.5 Statistical analysis

Any nutrient concentration values below the limit of detection were assigned the detection limit value for the purposes of statistical analysis. Detection limits of the various analyses are shown in Table 2.3. Dissolved available inorganic nitrogen (DAIN), being the sum of ammoniacal nitrogen (NH_4-N), nitrite nitrogen (NO_2-N) and nitrate nitrogen (NO_3-N) thus had a detection limit of 0.014 mg l^{-1} / 1.0 mmol m^{-3} (i.e. the sum of the detection limits of total oxidised nitrogen (TON (NO_2-N + NO_3-N) and ammoniacal nitrogen).

Statistical analyses were undertaken using the SPSS statistical software package (SPSS, 2002). Statistics, including the mean, 95% confidence interval for the mean (95%CI), standard deviation (SD), minimum, maximum and number of observations were used to provide statistical data summaries. Exploratory analysis also examined the normality of these data using the Shapiro-Wilk (S-W) and Kolmogorov-Smirnov (K-S) tests and the skewness statistic. The skewness value indicates the degree of positive or negative skew in a distribution, with normally distributed data typically exhibiting values in the range -1 to +1. Where distributions showed departures from normality, data transformations, such as $\log_{10}$, were examined.

Student's t-test (*t* statistic) and analysis of variance (ANOVA – *F* statistic) were used to explore significant differences between mean values. Student's t-test was used where the comparison was bivariate and ANOVA when more than two group means were under comparison. In both cases, the Levene statistic was used to assess the homogeneity of variance between the groups under comparison. A separate variance t-test result was used when the Levene test indicated that variances could not be considered equal between groups and a pooled variance test result used when variances could be considered equal. In the case of ANOVA, the outcome of the Levene test was used to determine the post-hoc multiple comparison test selected to indicate significant differences between pairs of mean values. Where variances could not be considered equal the Tamhane test result was selected whilst the Student-Tukey Honest Significant Difference (HSD) test was used in cases where variances could be considered equal.

In cases where data could not be considered normally distributed, non-parametric equivalent tests were applied. These tests are based on ranked values, the Mann-Whitney test (*U* - statistic) being used for bivariate comparisons and the Kruskall-Wallis test (c^2 - statistic) used in cases with more than two groups.

Bivariate regression routines were used to derive relationships between variables, for example to generate rating curves predicting discharge from stream level. The strength of relationships was assessed using the coefficient of determination (r^2) which measures the proportion (i.e. %) of variance in the dependent variable (*y*, e.g. discharge) explained by the independent or predictor variable (*x*, e.g. stream level). In all cases the r^2 value adjusted for degrees of freedom was quoted.

The statistical significance of all tests was assessed at the 95% confidence level (a = 0.05). This was achieved by comparing the calculated significance value for a particular test, *p*, with a. A statistically significant result (e.g. between mean values) is indicated when $p <$ a (i.e. $p < 0.05$).

3. Results

3.1 Hydrology – discharge, rainfall and drainage basin analysis

Hydrological monitoring results for the four open channel sections are summarized in Table 3.1. As the number of gaugings obtained was limited (*n*: 4 -7 observations), the data were combined with previous observations made in 2007 (Wyer et al., 2008). Analysis of channel cross-section parameters, such as width, depth and area, did not suggest major changes in channel cross profiles between the 2007 and 2009-2010 study periods. The combined data were analyzed to define rating curves covering the widest possible range of staff gauge readings at each site. Two obvious outliers were excluded from the Grands Vaux gauging site, collected during the summer of 2007 and discussed in Wyer et al. (2008). A nominal minimum stage value of 0.001 m (i.e. 1 mm) was assigned to a zero staff gauge reading at this site to allow rating curve analysis. One of the recent gaugings (25/05/2010) was excluded from the St Peter's Valley gauge site because the discharge recorded was negative, and could not, therefore, be used in the generation of power function rating curves. This was due to negative (i.e. net upstream) current directions recorded by the velocity meter at particularly low stage (0.13 m), which were probably associated with eddies across the profile. The results are summarized in Figure 3.1 and Table 3.2. The new gaugings were broadly in line with previous observations with the exception of St Peter's Valley. In the latter case the 2009-2010 gaugings produced consistently lower discharge values for a given stage (Figure 3.1). Inspection of individual discharge measurements suggested that the reduced discharge values were due to lower velocities rather than changes in channel cross section. This difference could reflect a variety of factors including differences between current meters and their use between the two studies as well as differences flow regime e.g. changes in downstream cross section affecting upstream water levels. However, the similarities in discharge values obtained between the two studies at other gauging sites suggest that operator and instrument differences are less likely to be the principal factor. Although rating curves based on the 2009-2010 data alone were assessed, it was felt that the curve based on the combined data was the most valid for the St Peter's Valley gauging site, covering the widest possible range of stream levels.

As in the 2007 study, power functions were applied for the St Brelade's stream, St Peter's Valley and Vallée des Vaux sites whilst, at the Grands Vaux site, which was a rectangular concrete section down stream of a bridge, a linear function was applied (Figure 3.1). All of the stage discharge ratings were statistically significant ($p < 0.001$) with levels of explained variance (r^2) exceeding ranging from 67.7 (St Brelade's) to 98.1% (Grands Vaux). Based on 15-minute stage levels generated from the pressure transducer records, stage exceeded the maximum values in Table 3.1 for the following proportions of the 2009 monitoring period: St Brelade's stream 1.16%, St Peter's Valley 0.00%, Vallée des Vaux 1.84% and Grands Vaux 0.02%. During the six month monitoring period in 2010, the proportions were: St Brelade's stream 1.11%, St Peter's Valley 2.25%, Vallée des Vaux 4.67% and Grands Vaux 1.63%. These values are relatively small and indicate that the ratings provided adequate coverage of the range of stream stage levels encountered at each site. The 15-minute records were also compared with bank full stage estimated from bank full profile measurements made in 2007. These values were not exceeded during the 2009 study period. However, they were exceeded for short periods during 2010 at the Vallée des Vaux (0.41%) and Grands Vaux (0.31%) gauge sites. This occurred during extremely wet weather conditions on 28th February 2010. The bank full stage values were assigned at these two sites during these periods when generating discharge values. The 15-minute stream stage values were used to generate average hourly time series and the discharge ratings were applied to these values to compute hourly time series of discharge for each gauge site. These values were used, in turn, to compute daily totals (m^3/d), matching the 06:30 daily discharge readings at the STW. The results are shown in Figures 3.2 (2009) and 3.3 (2010), which also includes plots of corresponding daily rainfall at the closer of the two Jersey Meteorological Department rain gauges. Figure 3.4 shows the operational daily discharge data Bellozanne STW and rainfall at the STW site. The steams show a typical seasonal hydrograph pattern of high discharge in the winter and early spring (i.e. February-March), when evapotranspiration rates are low and soil moisture levels are high, declining through the spring to low discharge in the summer when evapotranspiration rates and soil moisture deficit increase. Particularly high discharge was evident during late February and early March 2010 in response to heavy rainfall (Figure 3.3). As in the 2007 study, the time series for the STW shows a broadly similar pattern superimposed on a constant background discharge of around 2.0×10^4 m^3/d (Figure 3.4).

Table 3.3 summarizes drainage basin areas derived from the DEM for the catchments shown in Figure 2.1. Daily discharge volumes were estimated for each catchment based on these catchment areas. In the case of the St Brelade's (outlet 101) and St Peter's Valley (outlet 104) streams, daily discharge volumes were adjusted to reflect the catchment area at the outlet to the coast. In the case of site 107 (Town Brook/Weighbridge) the area down stream of the Grands Vaux/Vallée des Vaux confluence was assumed to behave like the Vallée des Vaux catchment. For the un-gauged brooks, daily discharge was estimated proportionally based on catchment areas and discharge in a neighbouring catchment. The La Haule A and B catchments were assumed to respond as per the St Brelade's stream catchment. Waterworks Valley discharge was estimated from the neighbouring St Peter's Valley discharge, whilst estimates for Bellozanne Valley were based on the Vallée des Vaux discharge record. The results are shown in Figures 3.6 and 3.7.

3.2 Nutrient (DAIN and DAIP) concentrations

3.2.1 Stream input sampling programme

A total of 22 sampling runs were undertaken in the two study periods, 12 in 2009 and 10 in 2010. Total numbers of DAIN results are listed in Table 3.4 and those for DAIP in Table 3.5. All DAIP values were in range (i.e. no values below the lower limit of detection or above the upper limit of detection). A total of 11 DAIN values had one parameter below the lower limit of detection and in all cases this was the NH_3-N concentration. All NO_2-N and NO_3-N determinations were within the detection limits.

The individual results are displayed in Figures 3.5 to 3.8. Tables 3.4 and 3.5 also summarize the mean and range and normality test results for the nutrient concentration data. The normality test results for DAIN suggest that this parameter broadly exhibits normality at all sites. This was also the case when all stream DAIN concentration were combined (n = 135, Skewness = -0.0378, K-S p = 0.2, S-W p = 0.2495). The mean was, thus, accepted as an adequate measure of central tendency for DAIN concentrations. The DAIN Results from the 2007 study showed similar distribution characteristics.

In contrast, the distribution of DAIP concentrations showed significant departure from normality in four of the streams (Table 3.5), all of which exhibited positive Skewness values > 1. The DAIP data were, thus, $\log_{10}$ transformed and Table 3.6 provides a corresponding summary. This analysis showed that DAIP distributions could be considered $\log_{10}$-normal in five of the inputs, with a sixth, Bellozanne Valley stream, showing improved Skewness (< 1) with $\log_{10}$ transformation. Further investigation of DAIP concentrations in the remaining input, La Haule B, showed the distribution here to be influenced by the maximum value, with the remaining data exhibiting a $\log_{10}$-normal distribution (n = 21, Skewness = 0.0564, K-S p = 0.2, S-W p = 0.9400). Combining all DAIP data (n = 135), $\log_{10}$ transformation reduced Skewness from 5.4606 to -0.1093, though K-S and S-W results still showed statistically significant departure from normality ($p < 0.05$). Based on these results, DAIP in stream inputs was considered to be $\log_{10}$-normal, with the geometric mean (GM) used as the corresponding measure of central tendency. Similar distribution characteristics were observed in the 2007 study.

One-way ANOVA was used to examine differences in mean DAIN concentrations between the seven stream inputs. The results revealed statistically significant differences between sites (Welch p = 0.000). Multiple comparisons using the relevant Tamhane test showed that the mean DAIN concentration in the La Haule B stream (12.67 mg/l) was significantly higher than at all other sites with the exception of Bellozanne Valley stream. Likewise, the mean DAIN concentration in Bellozanne Valley stream (13.91 mg/l) was significantly elevated to all other sites except the La Haule B stream. Mean DAIN concentrations showed no other statistically significant differences between sites. These patterns are evident in Figure 3.9.

A corresponding ANOVA for the $\log_{10}$ DAIP concentration data also showed statistically significant differences in GM values between stream inputs (Welch p = 0.000). In this case the GM DAIP concentration in the La Haule B stream (0.1177 mg/l) was significantly elevated compared to three other inputs, the St Brelade's (GM DAIP: 0.0781 mg/l), Waterworks Valley (GM DAIP: 0.0559 mg/l) and Bellozanne Valley streams (GM DAIP: 0.0560 mg/l). The only other significant difference was between St Peter's Valley stream (GM DAIP: 0.1141 mg/l) and Bellozanne stream. Again, these patterns are evident in Figure 3.9. Overall, the ANOVA results suggest that, in the context of surface water stream inputs to St Aubin's Bay, the La Haule B input stands out in terms of both DAIN and DAIP concentration, whilst Bellozanne Valley stream stands out in terms of DAIN.

3.2.2 STW effluent

A total of 159 DAIN and 157 DAIP results were available during the two study periods. The majority of these (n DAIN = 115, n DAIP = 113) were from STW operational data with an additional 44 results from samples collected as part of the current study. These comprised of 10 samples taken from the end of the outfall, 12 taken at First Tower and 22 at the STW. All DAIN and DAIP results were within the limits of detection. Table 3.7 summarizes the results from all samples and the Skewness/normality test results indicate that the distributions of DAIN and DAIP concentrations in the sewage effluent input to St Aubin's Bay can be considered normal. This was also the case in the 2007 study.

Table 3.8 summarizes DAIN and DAIP concentrations in samples of effluent collected at the three effluent sampling locations (i.e. the STW, the outfall and First Tower). One-way ANOVA was used to examine differences in mean DAIN and DAIP concentrations between the three sample collection sites (i.e. outfall, First Tower and STW). The results showed no statistically significant differences in either mean DAIN or DAIP concentrations between sites (DAIN: Welch p = 0.324, DAIP: Welch p = 0.230). This is consistent with the 2007 study results where no significant differences in mean DAIN or DAIP concentrations were found between the operational and study samples. Thus, the DAIN and DAIP results from all three sites were combined, allowing over 150 results to be used to define effluent DAIN and DAIP concentrations through the study periods. These are shown in Figures 3.5 to 3.8.

Figure 3.9 summarizes DAIN and DAIP concentrations in the stream and STW effluent inputs to St Aubin's Bay. This clearly illustrates the high nutrient concentrations found in the STW effluent compared to the stream inputs. For example the mean DAIN concentration in the effluent (29.33 mg/l) is over twice that found in any stream input (maximum mean DAIN: 13.91 mg/l (Bellozanne Valley stream)). The mean DAIP concentration in the STW effluent (3.6 mg/l) is over an order of magnitude higher than the

GM concentration found in any of the stream inputs (maximum mean DAIP: 0.1177 mg/l (La Haule B stream)).

3.2.3 Comparisons with 2007 study data

Table 3.9 summarizes the results of Student's t-tests used to compare the 2009-2010 mean DAIN concentrations with those recorded during the 2007 study. The only input to show any statistically significant difference in mean DAIN concentrations between the two studies was the St Peter's Valley input (Student's t-test $p < 0.05$, unequal group variances assumed), where the mean DAIN concentration in 2009-2010 (7.38 mg/l) was significantly lower than the corresponding 2007 value (10.63 mg/l). This could reflect differences in agricultural fertilizer application in the catchment in the intervening period.

The 2009-2010 mean DAIP concentrations were significantly lower than their 2007 counterparts in four of the seven stream inputs (Table 3.10). These were: St Brelade's stream, St Peter's Valley stream, Bellozanne Valley stream and the Weighbridge stream input. Single tailed t-test results, obtained by dividing the two tailed significance (p) values reported in Table 3.10 by 2, suggest that this significant reduction in mean DAIN was also present in all of the other stream inputs with the exception of the La Haule A stream (single tailed Student's t-test-p = 0.3089). In contrast, the mean DAIP concentration in the STW effluent was significantly higher in the 2009-2010 samples (3.57 mg/l) than the 2007 samples (3.24 mg/l). However, the absolute difference in mean concentrations between the two studies is comparatively small at all sites (0.02 mg/l – 0.07 mg/l in the brooks and 0.33 mg/l in the effluent).

3.3 Nutrient flux estimates

The flux of DAIN and DAIP from the stream and effluent inputs was assessed on a monthly basis. This was achieved by first assigning temporal mean concentration values. In the case of stream inputs each study period was divided into four-week periods and mean values assigned to each of these by using all results from the particular sample period plus the final result from the previous period, effectively producing a running mean. The mean DAIN values assigned were arithmetic, whilst the mean DAIP values were geometric for reasons discussed above. The values are plotted for each site in Figures 3.5 to 3.8. The larger number of results available for the STW effluent enabled assignment of weekly arithmetic mean DAIN and DAIP values.

Daily nutrient flux values (kg/d) were then calculated as the product of daily discharge (m^3) the corresponding mean concentration (kg/m^3) assigned to the relevant time period. Sum totals for DAIN and DAIP were then calculated for each month of the study, standardized to daily flux values (kg/d), to account for differences in the number of days in each month, particularly where the sampling period did not cover whole months. The results are shown in Figure 3.10 (DAIN) and Figure 3.11 (DAIP), whilst Figure 3.12 summarizes the corresponding monthly discharge estimates. Both DAIN and DAIP flux patterns are largely driven by discharge. In the brooks, particularly high nutrient loading is associated with high discharge volumes in November and in late winter/early spring (i.e. February and March), when soil moisture deficit and evapotranspiration rates will be lowest and runoff rates highest. In contrast, the STW effluent contributes a consistent flux to the bay; the background DAIN input from this source being around 600 kg/d and the background DAIP around 70 kg/d. These values are then exceeded in response to rainfall. Figure 3.13 shows monthly

DAIN and DAIP concentrations, calculated by dividing the total monthly load for each input by the total monthly discharge. The DAIN concentrations in brooks show consistently high concentrations associated with the La Haule B and Bellozanne Valley inputs, along with a seasonal pattern of maximum concentrations during late winter/spring, which tend to decline progressively to a minimum during the summer, followed by a autumnal increase. These patterns reflect vegetation growth cycles and reinforce the DAIN flux pattern associated with the annual hydrograph (i.e. DAIN concentrations tend to be highest when runoff is also elevated). The Figure also highlights the high DAIN concentrations associated with the STW effluent, reaching a peak concentration in May. Variations in effluent DAIN concentration are likely to reflect changes in the treatment regime with respect to DAIN rather than seasonal variations. This is shown in the pattern of DAIP concentrations in the effluent, which do not show large temporal variations (Figure 3.13). Seasonal variations in DAIP concentrations in the stream inputs appear less well defined than DAIN and tend to vary between sites.

Figure 3.14 summarizes the total monthly discharge and nutrient flux estimates for all stream inputs combined and the STW effluent. The discharge of surface water runoff via the brooks shows greater temporal variation than the STW effluent, reflecting seasonal variations in hydrological conditions. Thus, in winter/spring months when runoff is greatest the proportion of discharge via the brooks tends to exceed 50% (maximum 73% in November). This again illustrates the constant nature of the STW discharge to St Aubin's Bay. This pattern is reflected in the DAIN loading from the brooks, which reached a maximum proportion of 57.9% in March despite the lower DAIN concentrations associated with the brooks when compared with the STW effluent. In contrast, during the summer months, when runoff via the brooks is lowest, the DAIN loading is dominated by the STW effluent, which typically generates over 80% of the monthly load. Figure 3.14 clearly demonstrates that the DAIP loading to St Aubin's Bay is dominated by the STW effluent (93.58% to 99.13% of total load). This largely reflects the high DAIP concentrations found in the STW effluent compared to the brooks. The DAIP loading pattern, thus, reflects the discharge regime at the STW rather than the brooks and provides a constant background DAIP input to St Aubin's Bay.

Table 3.11 compares the total discharge, DAIN and DAIP loading estimates for the current study with those derived previously in 1997 and 2007. Overall discharge estimates show similar orders of magnitude, the current study being between the 1997 and 2007 estimates. The proportional breakdown between the brooks and STW effluent is also similar, particularly when comparing the current study with the 2007 results. Total DAIN loading estimates also display similar orders of magnitude. Again, the 2007 study DAIN results compare most closely with the current study, reflecting similarities in the discharge pattern. However, the proportional DAIN loading from the brooks (28.35%) is lower than that observed in 2007 (35.08%). The DAIP loading figures also show similar orders of magnitude and proportional distribution between the brooks and STW effluent. The DAIP load estimates for the current study and 2007 are particularly close and both are lower than the 1997 study estimates. This reflects changes in the STW effluent with respect to DAIP, since the STW effluent dominates the DAIP loading consistently accounting for over 95% of the total DAIP load.

A comparison of monthly load estimates for the brook and STW inputs from the 1997, 2007 and current studies is shown in Figure 3.15. Monthly discharge magnitudes in the current study were more similar to those from 1997, but all three studies show similar seasonal trends with discharge decaying from maximum values in February/March through the summer months as runoff declines and evapotranspiration increases. The DAIN flux patterns also show similar trends between studies, though the 2007 study showed the highest absolute DAIN loads, reflecting the higher discharge. The DAIP loadings in the current study were of similar magnitude to those estimated in 2007, which were much lower than the estimates from 1997. This reflects a significant reduction in DAIP concentrations in STW effluent since 1997 reported in the 2007 study (Wyer et al, 2008). This may reflect a general reduction in use of phosphorus compounds in detergents entering the wastewater treatment process over the past 12 years.

3.4 Offshore survey results

A total of eight full sampling runs were undertaken offshore in the two study periods, three in 2009 and five in 2010. Total numbers of DAIN, DAIP, DRS and chlorophyll *a* results are listed in Tables 3.12 to 3.15. During all eight surveys, 20 samples were collected from zone B (i.e. within St. Aubin's Bay). A total of 15 samples were collected from zone C during the first seven surveys, with 13 zone C samples collected during the final survey on 28/06/10.

Tables 3.12 to 3.15 also summarize the mean and range and normality test results for the nutrient and chlorophyll *a* concentration data. The normality test results for all four parameters showed that the distribution of concentrations showed significant departure from normality during at least two surveys. The data were, thus, $\log_{10}$ transformed to investigate whether this improved the normality of these data. For all four parameters, data from a greater number of surveys/zones showed a closer approximation to normal when $\log_{10}$ transformed, and Tables 3.16 to 3.19 provide corresponding summaries. Similar distribution characteristics were observed in the 1997 study for the nutrients (i.e. DAIN, DAIP and DRS) although the normality of chlorophyll *a* concentrations during the 1997 surveys was not improved by $\log_{10}$ transformations. Consequently, geometric mean concentrations represent the most appropriate measure of central tendency for the 2009/10 offshore data and used to populate the CSTT models (see Section 4). Note, however, that comparisons of chlorophyll *a* between 1997 and 2009/10 are comparing the arithmetic mean of data from 1997 with geometric mean data from 2009/10.

The geometric mean, 95% confidence interval and range of DAIN, DAIP, DRS and chlorophyll *a* concentrations in zones B and C from each survey are shown in Figures 3.16 to 3.19 whilst Figures 3.20 and 3.21 show the temporal trends of GM DAIN, DAIP, DRS and chlorophyll *a* concentrations (note that the data from the abandoned survey from 28/07/09 and the depth profile survey on 14/08/09 are omitted from Figures 3.20 and 3.21 due to the low sample numbers). Note that the data presented in these figures include one potentially anomalous sample result (site C7) collected from zone C on 28/06/10. Nutrient concentrations in this sample were 15.9 mmol m^{-3}, 16.4 mmol m^{-3}, and 3.6 mmol m^{-3} of DAIN, DAIP and DRS respectively, well in excess of any other sample collected from zone C during this survey or, indeed, the maximum zone C concentrations from other growing-season surveys. Consequently, it is likely that this sample was contaminated and not typical of zone C. Tables 3.16 to 3.18 also include statistical summaries for zone C on 28/06/10 excluding this anomalous result.

With the exception of zone B during the survey undertaken on 01/03/10 (i.e. before the phytoplankton growing season), the GM concentrations of DAIN in zones B and C were below the CSTT critical threshold of 12 mmol m^{-3}, indicative of hypernutrification (Figure 3.16; Figure 3.20; Table 3.16). Indeed, the only individual samples observed to exceed the 12 mmol m^{-3} threshold were from zone B during the survey on 01/03/10 (Figure 3.16). Geometric mean concentrations of DAIP also exceeded the CSTT threshold of 0.2 mmol m^{-3} in both zones B and C during this survey and also during the following survey on 29/3/10 although concentrations during the later survey were lower, indicating the start of nutrient uptake (Figure 3.17; Figure 3.20; Table 3.17). However, some individual samples in both zones B and C also exceeded the threshold during surveys on 11/08/09, 26/04/10 and 07/06/10 (Figure 3.17). Given both the DAIN and DAIP thresholds were exceeded during the winter (i.e. non-phytoplankton-growing season) these surveys therefore indicated hypernutrification in zone B. The high winter concentrations of DAIN and DAIP followed by a rapid decrease in concentrations as the phytoplankton spring bloom begins (Figure 3.20) is expected and replicates the pattern observed in 1997.

DRS concentrations displayed a decrease from maximum concentrations in each zone during the 01/03/10 survey to a minimum in late April 2010 (Figure 3.18; Figure 3.21; Table 3.18). An increase from the minimum values after late April 2010 is reflected in the increasing trend of DRS between the beginning of June and mid-August during 2009. The rapid decrease in DRS concentrations during the early phytoplankton season, followed by a more gradual increase, is also expected and reflects uptake by siliceous organisms during the spring bloom.

Excluding the anomalous data for sample C7 on 28/06/10 results in slightly lower GM concentrations for DAIN, DAIP and DRS (Tables 3.16 to 3.18; Figures 3.20 and 3.21)

No individual samples collected offshore from either zones B or C exceeded the CSTT critical threshold for chlorophyll *a* of 10 mg m^{-3}, thus the GM concentrations were all below the threshold (Figure 3. 19; Figure 3.21; Table 3.19). Consequently no actual eutrophication, as indicated by chlorophyll *a* concentrations, was observed. The increase in chlorophyll *a* concentrations during the early April 2010 survey (Figure 3. 19; Figure 3.21) reflects the spring bloom of phytoplankton as available nutrients are utilised. Levels decrease thereafter as a dynamic equilibrium between primary productivity and nutrient availability limits further increases in concentrations. No evidence of an expected autumn bloom of phytoplankton is discernable from the data, although it is possible that this may have taken place after the latest survey in the growing season, undertaken in mid-August 2009.

Student's t-test results comparing the $\log_{10}$ transformed DAIN data between zones B and C showed statistically significant differences in offshore surveys 3 and 5-7 with greater GM concentrations in zone B (Table 3.20). No statistically significant differences were present between the GMs during the first two and the last offshore surveys, whilst the survey undertaken on 07/06/10 (offshore 8) displayed a statistically significant difference albeit with a greater GM concentration in zone C (Table 3.20). Interestingly, all four of the surveys that did not display a significant elevation in DAIN, were undertaken during the month of June. For DAIP, Student's t-tests between zone B and C data showed the GM in zone B was significantly greater than in zone C during offshore surveys 5, 6 and 8 whilst the GM concentration in zone C was significantly greater than in zone B during survey 3, the latest survey undertaken during the phytoplankton growing season i.e. in August (Table 3.21). The GM DRS concentrations in zone B were significantly elevated compared to zone C during all surveys with the exception of surveys 2 and 9, both undertaken in late June (Table 3.22). Mean chlorophyll *a* concentrations in zone B were significantly elevated compared to zone C during the first two offshore surveys (both June 2009) and survey 7 (late April 2010) (Table 3.23).

3.4.1 Comparison with 1997 survey data

Plots comparing the GM nutrient concentrations from the 1997 and 2009/10 surveys are shown in Figures 3.22 to 3.25. Broadly, the pattern of GM DAIN concentrations from 2009/10 was similar to those from 1997 with high winter concentrations and lower concentrations during the growing season (Figure 3.22). However, the 2010 data showed the decrease in concentrations associated with the spring phytoplankton bloom started earlier (sometime during March 2010 as opposed to during April in 1997) but the decrease itself was more gradual than during 1997. The peak winter GM in zone B was greater in 2010 than in 1997 although in zone C the GM from 1997 was greater. Summer concentrations were similar between all surveys (Figure 3.22). The temporal pattern of GM DAIP concentrations from both zone B and zone C during the 2009/10 surveys were similar those observed during 1997 with the decrease in concentrations to below the CSTT hypernutrification threshold occurring at a similar time of the year (i.e. concentrations were below 0.2 mmol m^{-3} by the start of May) (Figure 3.23). Geometric mean DAIP concentrations in zone C during 2009/10 were of a similar magnitude to those observed in 1997, although there was a larger discrepancy between summer concentrations in zone B, where 1997 concentrations were higher. DRS concentrations, however, showed a greater variation between 1997 and 2009/10 with concentrations from the latter set of surveys being greater than during 1997 (Figure 3.24). The decrease between elevated winter concentrations and lower growing season concentrations occurred over a shorter timescale during 2010 whilst the subsequent increase in concentrations after the spring bloom was more pronounced (Figure 3.24).

Comparison of the mean 1997 chlorophyll *a* data against the GM 2009/10 data (Figure 3.25) showed that concentrations were similar with the exception of the late March 2010 survey, where GM chlorophyll *a* concentrations in both zones B and C were double those of the other surveys. It is possible that these elevated concentrations are indicative of the spring bloom of phytoplankton during 2010, corresponding with decreased DAIN, DAIP and DRS concentrations which were yet to reach the relatively low summer equilibrium concentrations. Such an elevation was not observed in the 1997 data and this may be due to the more rapid attenuation of nutrients during that year meaning that the spring bloom peak in chlorophyll *a* concentrations occurred between surveys.

Since there were no offshore surveys between mid August and the end of October, it is not possible to identify whether chlorophyll *a* concentrations rose to an autumn peak, as was the case in 1997, or if DAIN and DAIP concentrations began to increase as primary production decreased towards late autumn.

3.5 Depth profile data

In addition to surface samples, a series of samples were also collected from selected sites at specified depths during three surveys, undertaken on 14/8/09, 7/6/10 and 28/6/10. Between four and six sites within zone B situated on all three transects were sites selected for depth profiling, with four sites in zone C, running approximately north to south along a line extending from the zone B central transect (Figure 2.4). Samples were collected from the surface, one-third depth, two-thirds depth (depth measured at the time of arrival at the site), and at the seabed. During the two 2010 surveys, additional data was collected through the water column using a multi-parameter water quality sonde.

During all three depth profile surveys, DAIN concentrations did not display a consistent pattern of change with depth although during the first depth profile survey, undertaken on 14/8/09, the surface concentration of each profile was the lowest of each set of four samples. However, the GM DAIN concentrations for surface samples from each zone displayed the lowest concentrations during all three profile surveys (Tables 3.24 to 3.26). This was probably due to conditions being most favourable for phytoplankton growth (i.e. uptake of nutrients) in the upper water column where light penetration is at a maximum. This pattern was not consistently repeated by DAIP, or DRS concentrations (Tables 3.24 to 3.26), although this may be due to the fact that DAIN was the limiting nutrient for phytoplankton growth (Section 4.2).

Chlorophyll *a* concentrations observed during the first depth-profiling survey (14/08/09) were amongst the lowest observed during any offshore surveys, with the majority of samples being below the limit of detection (i.e. 0.5 mg m^{-3}) and displaying little or no variation with depth. The surface GM chlorophyll *a* concentration in zone C was slightly greater than at the other depths, but the difference was minimal (Table 3.24). During the second profile survey (07/06/10), GM chlorophyll *a* concentrations were greatest at the surface in both zones, perhaps reflecting the better conditions for growth at the sea surface compared to lower in the profile (Table 3.25). Geometric mean chlorophyll *a* concentrations during the final depth survey (28/6/10) did not display a consistent pattern, with the lowest concentration at the surface in zone B whilst the highest GM concentration was at the surface in zone C (Table 3.26).

During the two depth profile surveys undertaken in 2010 (02/06/10 and 26/06/10), vertical profile measurements were collected for temperature (˚C), dissolved oxygen (% saturation and mg l^{-1}), conductivity (µS cm), salinity (ppt) and turbidity (NTU) (data available for 26/06/10 survey only). Profiles for temperature, dissolved oxygen (% saturation and mg l^{-1}) and salinity are shown in Figures 3.26 (07/06/10) and 3.27 (28/06/10). These profiles did not identify any vertical stratification of temperature, dissolved oxygen, or conductivity/salinity during both surveys. There was also little difference between the ranges of data collected in zones B and C (Table 3.27). The recorded data for turbidity from 26/06/10 were all below zero (i.e. negative) with the exception of two seabed readings at sites B30 and B34 (Table 3.27), which were possibly a result of the disturbance of sediments when the probe hit the seabed. The sonde was calibrated prior to delivery to the States of Jersey and the negative values are therefore likely to be indicative of very low to zero turbidity.

3.6 Beach survey data

The GM concentrations of DAIN, DAIP, DRS (Tables 3.28 to 3.30; Figures 3.28 and 3.29) and mean chlorophyll *a* (Table 3.31; Figure 3.29) were all generally greater and more variable within the nearshore surf zone than observed offshore. As in the offshore survey, the highest GM nutrient concentrations were observed outside the phytoplankton-growing season. The GM DAIN concentrations exceeded the 12 mmol m^{-3} winter threshold during both surveys carried out during October 2009 and all surveys between 08/02/10 and 12/04/10. Otherwise, nearshore GM DAIN concentrations in the nearshore zone were below the threshold. During the surveys undertaken before October 2009, no individual observed values exceeded the CSTT DAIN threshold although the upper 95% confidence limit of

DAIN concentrations on 14/09/09 did exceed the threshold[1] (Figure 3.28). The first three surveys of 2010 displayed nearshore concentrations of DAIN above the winter threshold at all sample points whilst thereafter all but the final two surveys displayed at least one sample point with a DAIN concentration in excess of the threshold (Table 3.28; Figure 3.28).

The CSTT (1997) winter DAIP threshold of 0.2 mmol m^{-3} was exceeded by the nearshore GM DAIP concentrations from all surveys, with the exception of the first survey on 01/06/09 (Table 3.29; Figure 3.28). The highest nearshore DRS concentrations and GMs were observed outside of the phytoplankton-growing season (Table 3.30; Figure 3.29) and followed a trend similar to nearshore DAIN concentrations.

GM chlorophyll *a* concentrations during the 2009 surveys (Table 3.31; Figure 3.29) were well below the summer 10 mg m^{-3} threshold during the first two surveys on 01/06/09 and 15/06/09, although after this date concentrations either approached or exceeded the threshold, with the exception of a dip in concentrations on 10/08/09. The highest nearshore GM chlorophyll *a* concentrations were observed during surveys on 02/09/09 and 27/10/09 with GM concentrations of 22.8 and 23.1 mg m^{-3} respectively (Table 3.31; Figure 3.29). The nearshore chlorophyll *a* GM concentrations exceeded the CSTT 10mg m^{-3} threshold during two of the 2010 surveys, on 08/02/10 and again on 26/04/10, this latter survey displaying all 5 nearshore samples above the threshold (Table 3.31; Figure 3.29).

Figures 3.30 and 3.31 show the GM nearshore nutrient and chlorophyll *a* concentrations from the 2009/10 surveys plotted against 1997 survey data collected from the same five nearshore sample points. The nearshore DAIN concentrations collected between February and May 2010 displays an earlier, yet slower, decline of GM concentrations when compared to the 1997 data, which displays a sudden decline between two surveys, although the fall to below the 12 mmol m^{-3} CSTT (1997) DAIN threshold occurred at the end of April during both 1997 and 2010 (Figure 3.30). This slower decline reflects a similar trend displayed by the offshore zone B and zone C data (Figure 3.22). Thereafter, there were few differences between the 1997 and 2009/10 data (Figure 3.30). GM DAIN concentrations in the nearshore zone were generally lower and less variable than those observed in 1997 (Figure 3.30) whilst DRS concentrations were generally higher but followed a similar trend to 1997 data (Figure 3.31). Nearshore GM chlorophyll *a* concentrations during the 2009/10 surveys were more variable than during 1997 with the majority of surveys undertaken at a similar time of the year being greater during the 2009/10 surveys (Figure 3.31).

The higher nutrient and chlorophyll *a* concentrations in the nearshore zone may be due to a number of factors, including proximity to the catchment- and sewage-derived sources of nutrients, increased turbulence facilitating greater mixing of nutrients and resuspension of settled particulates, presence and concentration of macro-algae within the water column and local differences in factors relating to phytoplankton growth (e.g. warmer temperatures in the shallower water). Such factors may also explain the wide variability in concentrations between sample sites during the same survey, with varying proximity to the nutrient sources or sinks of free-floating macro-algae or, indeed, localised blooms of phytoplankton relative to tidal, wind and/or wave induced currents, explaining these differences. It is important to note that samplers often reported large amounts of macroalgae

[1] Note that the low number of samples (n = 5 during all surveys) results in a relatively wide 95% confidence interval.

within the water column during some sampling events and it is possible that these macro-algae within samples contribute to the high chlorophyll *a* concentrations observed.

4. Prediction of trophic state

The CSTT (1994; 1997) recommended methodology provides a simple mathematical model to predict steady state nutrient concentrations. Using these predictions, a further model is provided to predict the potential maximum biomass of phytoplankton. The models described in CSTT (1994) were applied in Stapleton and Kay (1997) using data collected during the 1997 field studies, which form the basis for the current study. This section describes the models and their population using the empirical data collected during the 2009/10 field surveys. It should be noted that, whilst the models themselves were not changed in the 1997 revision of the CSTT advice (CSTT, 1997), some amendments to recommended interpretation of model outcomes were made. These are highlighted where relevant.

4.1 Steady state nutrient concentrations

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

$$S = S_o + \left(\frac{(s_i + s_d)}{(E \times V)} \right) \quad \text{mmol m}^{-3} \qquad 8$$

Where:

- S is the predicted steady state nutrient concentration in zone B
- S_o is the nutrient concentration in zone C (mmol m^{-3})
- s_i is the sum 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.

The relative exchange rate (E = 0.599 d^{-1}), calculated using a computer-based three-dimensional numerical hydrodynamic model (Falconer and Kolahaldoozan, 1998), and volume of the bay at mid-tide level (V = 6.33 x 10^{7} m^{3}) used in the original model predictions reported in Stapleton and Kay (1997), were used in the current estimates. The relative exchange rate used was for a neap tide to provide consistency with the CSTT (1994; 1997) guidance of using a neap tidal excursion to identify the extent of zone B. This indicates that approximately 97% of the enclosed fluid volume of St Aubin's Bay is exchanged every five tides (Falconer and Kolahaldoozan, 1998). The volume of the bay was estimated from Admiralty chart data. The nutrient flux from the different inputs was derived from data collected during 2009/10 as part of the beach surveys as described in Sections 3.1 to 3.3.

The results of the model calculations are shown in Table 4.1 and Figures 4.1 and 4.2 together with the results for comparable surveys undertaken in 1997.

Predicted steady state DAIN concentrations (S_{DAIN}) using 2009/10 survey data were greater than for the equivalent 1997 surveys during the summer months except for the mid-August 2009 survey (Table 4.1; Figure 4.1). Whist it is difficult to compare this survey (11/08/09) with previous data due to the fact that the survey was undertaken between two survey dates from 1997 (i.e. 29/07/97 and 09/09/97), the 2009 predicted DAIN concentration was lower than either of the 1997 surveys. During March 2010, when hypernutrified conditions were observed in zone B at the beginning of the month, the predicted steady-state DAIN concentrations were lower than during the equivalent surveys from 1997.

With the exception of the 26/04/10 survey (survey 7), the predicted steady state DAIP concentrations (S_{DAIP}), using 2009/10 data, were all lower than the equivalent 1997 surveys (Table 4.1; Figure 4.1), reflecting the lower DAIP inputs (primarily from the STW effluent) during 2009/10.

Comparisons between the observed and predicted DAIN and DAIP concentrations (Figure 4.2) show that, with the exception of the early March 2010 survey, observed DAIN GM concentrations in St. Aubin's Bay were lower than predicted by the CSTT model. All observed DAIP GM concentrations in St. Aubin's Bay were lower than the CSTT model predicted values (Figure 4.2). This suggests that nutrient inputs are being dispersed to a greater extent than the neap tide conditions modelled and/or being utilised by the marine flora.

4.2 Maximum biomass of phytoplankton

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

$$X_{\max} = X_o + (q \times S) \quad \text{mg m}^{-3} \qquad 9$$

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 each nutrient, 1.1 to 2.8 mg chl (mmol DAIN)$^{-1}$, 50 to 100 mg chl (mmol DAIP)$^{-1}$.

$X_{\max}$ can be estimated using both S_{DAIN} and S_{DAIP}. The model estimates for 1997, reported in Stapleton and Kay (1997), used the two figures quoted by CSTT (1994) for phytoplankton yield (i.e. q) as a minimum and maximum, thus presenting $X_{\max}$ as a range. The yield of phytoplankton provided by CSTT (1994; 1997) was based on a study presented by Gowen et al. (1992), undertaken in Scottish west coast sea lochs, with the 'minimum' yield being the median yield observed during these studies, and the 'maximum' representing the 90 percentile value. However, the 1997 revision of the CSTT advice added a recommendation that the median yield (i.e. 1.1 mg chl (mmol DAIN)$^{-1}$, 50 mg chl (mmol DAIP)$^{-1}$)[2] is used for the purposes of the assessment. However, to provide data comparable with the 1997 modelling results, both the median and 90 percentile values are used to provide a range for

[2] Note that the CSTT 1997 report remains silent regarding whether the median yield from DAIP was the lower of the two values quoted. The DAIP yield was also not discussed in Gowen et al. (1992). Given the similarity in the format the yield values for DAIN and DAIP are presented within CSTT (1194; 1997) it is assumed here that the 50 mg chl (mmol DAIP)$^{-1}$ yield is the median value for DAIP.

X_{max} for the 2009/10 data. The results of the calculations are presented together with comparable results from the 1997 surveys in Table 4.2.

Comparison of the increase in biomass (i.e. $q.S$) shows that during all 2009/10 survey DAIN is the limiting factor for growth since $q.S$ for DAIN is smaller. This is to be expected since DAIN is the usual limiting factor in marine conditions. Thus, control of the DAIN concentrations in St. Aubin's Bay is key to managing phytoplankton growth within the bay.

The minimum DAIN X_{max} concentration (i.e. that calculated using the median yield values) exceeds the CSTT (1997) 10 mg chl m^3 threshold during the two March 2010 surveys (surveys 5 and 6) when hypernutrified conditions prevail (Table 4.2; Figure 4.3), although the high nutrient concentrations observed during these surveys (Tables 3.2 – 3.4; Figures 3.20 and 3.21) suggests that conditions were not yet suitable for phytoplankton growth. The threshold was not exceeded by the predicted estimates during the summer months when using the median yield value recommended by CSTT (1997).

During surveys undertaken in late June (both 2009 and 2010) and mid-August, the maximum DAIN X_{max} estimate (i.e. that calculated using the 90 percentile yield values) was below the threshold indicating that eutrophication would not develop even under ideal conditions for phytoplankton growth (Table 4.2; Figure 4.3). The predicted range of DAIN X_{max} spans the threshold between the end of April to the Beginning of June (i.e. the minimum (median yield) estimate) remains below the 10 mg m^{-3} threshold whilst the maximum (90%ile yield) estimate exceeds the threshold. Generally, the predicted range of 2009/10 X_{max} was greater than the 1997 data during the growing season, although it was lower during the two March 2010 surveys (Table 4.2; Figure 4.3).

Comparison of the predicted ranges of DAIN X_{max} with the observed GM chlorophyll *a* concentrations from the 2009/10 surveys shows that the observed GM concentrations were below the predicted minimum DAIN X_{max} values during all surveys (Figure 4.4). This suggests that other factors are also limiting chlorophyll *a* with St. Aubin's Bay.

The predicted DAIP X_{max} ranges for 2009/10 (Table 4.2) were all lower than comparable surveys from 1997 with the exception of the survey carried out at the end of April 2010. These lower ranges of X_{max} are a reflection of the lower predicted steady state DAIP concentrations arising for the decreased DAIP inputs (primarily from Bellozanne STW). However, since phytoplankton growth is limited by DAIN, the predicted DAIP X_{max} concentrations would not be realised above the maximum DAIN X_{max} concentrations (Table 4.2).

4.3 Relative rate of light controlled growth

No new data were collected to populate the CSTT (1997) model for calculating the relative rate of light controlled growth. Hence, the results of calculations presented in Stapleton and Kay (1997), which was based on generic data provided in CSTT (1997), remain the best available data to indicate when maximum biomass may be realised:

$$\mu = \alpha \times \left(\frac{m_2 \times I_o}{(\lambda \times h) - I_c} \right) \quad d^{-1} \qquad 10$$

where:

μ	is the relative rate of light controlled growth (d^{-1})
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 (m^{-1}). This can be calculated using Equation 11.
h	is the mean depth of the defined volume
I_c	= $12\mu E\ m^{-2}\ s^{-1}$, is the compensation irradiance, the minimum allowing phytoplankton growth.

and:

$$\lambda = \frac{\Delta \ln(I_z)}{\Delta z} \quad m^{-1} \quad \text{for depths greater than } \frac{1}{\lambda} \qquad 11$$

where:

λ	is the diffuse attenuation coefficient for most downwelling PAR (m^{-1})
I_z	is submarine downwelling PAR
z	is the depth (m).

In the absence of suitable data to solve the equation for the relative rate of light controlled growth[3], 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.;

$$\mu > (E + L) \qquad 12$$

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.

The model indicates maximum biomass may be realised during neap tides in March and during both spring and neap tides in June (Table 4.3). This implies that conditions within St. Aubin's Bay gradually become suitable for maximum chlorophyll biomass development: first intermittently, during neap tides in March; gradually extending over time to encompass wider tidal ranges; finally extending over the whole spring-neap cycle by the beginning of June. The fact that suitable conditions for phytoplankton growth may not be fully realised until June, and that the high winter nutrient concentrations are depleted before the end of

[3] Attempts were made to measure the diffuse attenuation coefficient (λ) using a Skye Instruments quantum sensor during the 1997 surveys. 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.

April may limit the growth of phytoplankton. This may also explain the lower than predicted observed chlorophyll *a* concentrations.

4.4 The trophic status of St. Aubin's Bay

Under the terms of the UWWTD (Anon, 1991), three key questions need to be addressed.

- Are the waters into which a 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 that is eutrophic or displays the potential to become eutrophic.

CSTT (1997) consider a coastal water is not adversely affected by a discharge if, for zone B:

i) there are no observations showing winter 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 empirical evidence, or likelihood, of <u>hypernutrification</u>;

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

ii) there are no observations showing <u>summer</u> chlorophyll *a* >10 mg m^{-3}, nor do equations 10 and 11 predict such concentrations when conditions allow phytoplankton growth to exceed losses: that is, there is no evidence, or likelihood, of <u>eutrophication</u>;

or if, eutrophication has been demonstrated or predicted,

iii) the application of secondary treatment[4] 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 4.4 summarises the assessment of points (i) to (iii), which has been completed using zone B and nearshore data.

4.4.1 Winter hypernutrification

The 1997 revision of the CSTT report changed criterion (i) above to read: '*no <u>winter</u> hypernutrification*' compared to '*no <u>summer</u> hypernutrification*' suggested in the first edition of the report (CSTT, 1994). Only zone B, during the survey of 01/03/10 displayed observed GM and individual sample DAIN concentrations above the CSTT 12 mmol m^{-3} threshold (in the presence of >0.2 mmol m^{-3} DAIP) indicative of hypernutrification, although it is perhaps significant that further offshore in zone C, the GM concentration was lower (zone B = 14.8 mmol m^{-3}, zone C =10.9 mmol m^{-3}; Table 3.16). The CSTT predicted steady-state DAIN

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

concentration for zone B was also above the CSTT threshold for 01/03/10. However, both observed and predicted concentrations using 1997 data indicated hypernutrification until the end of March. Within the nearshore zone, observed GM DAIN concentrations were above the threshold until after the mid-April survey although individual samples exceeded this threshold until 08/06/10 (Table 3.28). Thus, winter hypernutrification was both observed and predicted.

4.4.2 Eutrophication

The revised version of the CSTT report (1997), clarified the application of the chlorophyll *a* 10 mg m^{-3} threshold as applying '*absolutely only to the summer concentrations*' (p22, CSTT, 1997). It also states that chlorophyll *a* concentrations exceeding this threshold during the spring, when algal blooms develop naturally, '*are not deemed evidence of eutrophication unless there is a substantial shift away from diatoms in the species balance*' (p22, CSTT, 1997).

Observed zone B chlorophyll *a* concentrations did not exceed the CSTT 10mg m^{-3} threshold indicative of eutrophication at any time during the sampling period. The highest chlorophyll *a* concentration observed during the 2009/10 surveys was 5.1 mg m^{-3}, although this was during the survey in late March 2010 (Figure 3.19). Predicted maximum phytoplankton biomass, estimated using DAIN concentrations, suggest that the 10 mg m^{-3} threshold would be exceeded during the two March 2010 surveys when using the recommended median phytoplankton. This would extend through to early June if the higher 90 percentile yield of phytoplankton chlorophyll *a* was used.

Observed chlorophyll *a* concentrations in the nearshore zone exceeded the 10mg m^{-3} threshold on several occasions during the summer although some of this concentration may be due to macro-algae entrained within samples within the more turbulent surf zone.

Thus, in zone B eutrophication was not observed, nor was potential eutrophication indicated by predicted chlorophyll concentrations if the median chlorophyll *a* yield was used. If, however, the 90 percentile chlorophyll *a* yield is used to predict the phytoplankton chlorophyll *a*, the late April and early June surveys exceed the threshold (albeit the June surveys by 0.2 mg m^{-3}). If these surveys are deemed to be 'summer' then potential eutrophication is suggested. In the immediate nearshore zone, eutrophic conditions, as suggested by chlorophyll *a* concentrations above the 10mg m^{-3} threshold were observed during the summer period.

4.4.3 Impact of nutrient removal from effluent

Predicted steady state DAIN concentrations and chlorophyll *a* concentrations in zone B (i.e. assuming a concentration of 10mg l^{-1} in the Bellozanne effluent) are provide in Table 4.5.

Two exploratory analyses have been undertaken. First, the effluent DAIN concentration needed to achieve a 1mg m^{-3} decrease in chlorophyll *a* concentrations is calculated. This is the minimum reduction deemed necessary by CSTT (1997) for nutrient removal to have an impact on the trophic status of a receiving water (Table 4.6). Second, the effluent DAIN concentrations required to achieve a zone B chlorophyll *a* concentration of 10 mg m^{-3} (i.e. the CSTT eutrophication threshold) was estimated (Table 4.7). Both analyses used the CSTT (1997) models described in equations 8 and 9 and are based on the 'worst-case' phytoplankton chlorophyll *a* yield of 2.8 mg chl (mmol DAIN)$^{-1}$.

Table 4.6 shows effluent DAIN concentrations necessary to achieve a 1 mg m^{-3} decrease in chlorophyll *a* concentrations in zone B. DAIN concentrations required to achieve a 1mg m^{-3} reduction in chlorophyll *a* under conditions experienced during the offshore surveys ranged between 17.5 mg l^{-1} and 26.0 mg l^{-1}, with the lowest concentrations being required during March 2010. However, a reduction of 1mg l^{-1} chlorophyll *a* would not result in zone B concentrations below the CSTT 10 mg l^{-1} eutrophication threshold during these two surveys or that undertaken at the end of April 2010, although it is uncertain whether conditions would allow the maximum yield to be realised. During all other surveys, an effluent DAIN concentration of <19.5 mg l^{-1} would result in at least a 1mg l^{-1} reduction in predicted chlorophyll *a* in zone B. Note that the predicted reduction in chlorophyll *a* would be lower than 1 mg m^{-3} for any given concentration if the median phytoplankton chlorophyll yield (1.1 mg chl (mmol DAIN)$^{-1}$) was used in the modelled estimates.

Table 4.7 shows the results of the analysis to determine the DAIN concentration in the Bellozanne effluent for the predicted chlorophyll *a* concentrations in zone B to equal the 10 mg m^{-3} CSTT eutrophication threshold. The table shows that, during the surveys undertaken in March and April 2010, even if the DAIN concentration of the effluent was zero, it would not be possible to reduce the predicted chlorophyll *a* concentration in zone B to below the threshold. However, again, conditions are unlikely to allow the maximum yield to be realised. During the remaining surveys, the required DAIN concentration varied between a minimum of 26 mg l^{-1} (07/06/10 survey) and a maximum of 45.5 mg l^{-1} (11/08/09 survey).

4.4.4 Interpretation

The limiting nutrient for phytoplankton growth within St. Aubin's Bay was shown by the CSTT (1997) methodology to be DAIN, which is typical of most marine waters. Observed DAIN and DAIP concentrations within the bay displayed hypernutrification at the beginning of March, whilst predicted DAIN concentrations were indicative of potential hypernutrification between March and the end of April. Winter hypernutrification can be expected in some nearshore waters and, in itself, is not necessarily a problem. Observed chlorophyll *a* concentrations were below the CSTT (1997) threshold indicative of eutrophication during all offshore surveys and the CSTT models indicated that predicted concentrations would not exceed the threshold during the summer when using the recommended median value for chlorophyll *a* yield from phytoplankton.

Thus, following the CSTT (1997) methodology, eutrophication was not present within St. Aubin's Bay.

However if the 'worst-case' 90 percentile phytoplankton chlorophyll *a* yield is used, eutrophication may potentially be present (i.e. is predicted using the CSTT models) during the early summer (i.e. April – beginning of June) although, clearly, there was no evidence that this was the case from observed data. The empirical survey data identified an elevation of chlorophyll *a* concentrations during the late March 2010 survey that could be a result of the spring bloom, but the zone B GM concentration was still well below the CSTT threshold. DAIN concentrations were decreasing at this time, approximately mid-way between the winter hypernutrified state and the relatively stable summer DAIN concentrations where the system is in dynamic equilibrium, suggesting that the primary production was utilising the available nutrients without causing eutrophic conditions. Dissolved reactive silicon concentrations were also decreasing during this period suggesting that the bloom includes diatoms, as expected. It is worth noting that a similar decreases of DAIN and DRS and increases in chlorophyll *a* were observed further offshore in zone C, suggesting that the impacts of the terrestrial inputs were limited. It is difficult to identify a precise time for the start and end of the spring bloom period due to the approximate monthly period between surveys. However, the end of April to the beginning of June is the key period, by which time the limiting DAIN concentration had reached its summer equilibrium concentration and DRS concentrations had started to rise again, indicating a slowing in diatom growth. Thus, perhaps only the slight exceedance of the 10 mg m^{-3} threshold by the worst-case predicted chlorophyll *a* concentrations becomes an issue of whether this is indicative of potential eutrophication.

The nearshore, surf zone data is more difficult to interpret since this zone is not catered for within CSTT although is particularly relevant in the Jersey situation since the outfall discharges at mid-tide level rather than being continually submerged. Thus, when the outfall is exposed, initial mixing may be limited, particularly on calm days. In such cases, it is possible that a buoyant treated effluent slick may form in the nearshore zone which experiences only partial mixing. Similarly, the streams that discharge into St. Aubin's Bay may form similar buoyant slicks. Due to the limited mixing which might be expected under such situations, this area might, in fact, fall within the CSTT (1997) definition of zone A (see Section 2.4.2) and it would perhaps be inappropriate to apply the CSTT thresholds. This study has clearly shown that DAIN, DAIP and chlorophyll *a* concentrations are elevated within this nearshore zone, although the contribution of macro-algae to the chlorophyll *a* concentrations in this zone may be an important factor. Despite high chlorophyll *a* concentrations in some samples collected from this nearshore zone, however, dissolved oxygen concentrations did not notably vary when compared to samples with low chlorophyll *a* concentrations. However, the presence of decaying macroalgae in the nearshore zone represents a risk to maintaining dissolved oxygen levels at appropriate levels. Thus, this area probably represents the zone most likely to experience oxygen depletion, which may be a result of eutrophication (i.e. the result of the decay of a nuisance algal bloom) or decay of macro-algae.

5. Conclusions

Both observed and modelled data indicated that hypernutrification was present within St. Aubin's Bay during early March 2010 whilst observed chlorophyll *a* concentrations were all below the CSTT (1997) threshold indicative of eutrophication. Predictions of chlorophyll *a* concentration using the CSTT (1997) recommended yield of chlorophyll from phytoplankton were also below the threshold during the key summer period. Consequently, the results suggest that St. Aubin's Bay is not subject to eutrophication.

However, if the 'worst-case' chlorophyll *a* yield presented by CSTT (1997) is used, the results might suggest eutrophic conditions could exist in St. Aubin's Bay around the beginning of June if it is presumed that the spring phytoplankton bloom has finished by this time. Even so, the predicted values are only slightly above the threshold and are likely, therefore, to be sensitive to the values used in the models. Changing the exchange rate to that for a spring tide, for example, would mean that the predicted chlorophyll *a* concentrations for the two early June surveys would no longer be above the CSTT eutrophication threshold.

High nutrient and chlorophyll *a* concentrations in the nearshore surf zone, however, suggest eutrophic conditions might periodically occur within this zone, although on most occasions it is limited to isolated sites rather than the entire stretch of shoreline. It is important to note that the CSTT (1997) advice does not deal specifically with the surf zone and application of the thresholds to this zone is therefore uncertain. Also, no nuisance algal blooms were reported during the surveys and although the thresholds were exceeded, the absence of such blooms coupled with no apparent impact on dissolved oxygen concentrations suggests eutrophication was not actually present.

Overall, empirical evidence and the CSTT recommended model predictions suggest that St. Aubin's Bay was not eutrophic, although the CSTT model predictions based on a worst-case phytoplankton chlorophyll yield suggest there is a small chance eutrophication may develop. The period where the bay is most at risk of eutrophication is during the summer equilibrium period when nutrient and chlorophyll *a* concentrations are low and the most sensitive to enrichment. The fact that summer nutrient and chlorophyll *a* concentrations were low during both the 2009/10 and 1997 surveys, coupled with the dominance of the DAIN flux to the bay by inputs from Bellozanne STW during the summer, suggest that the STW is not stimulating eutrophic conditions in the bay. Nevertheless, an assessment of whether improved removal of DAIN from the STW effluent would have an impact on predicted chlorophyll *a* concentrations in St Aubin's Bay suggested that a 1 mg m^{-3} decrease in chlorophyll *a* could be achieved by reducing the DAIN concentration in the Bellzoanne effluent to less than 17.5mg l^{-1}.

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Acknowledgements

The authors are grateful to Duncan Berry, Steve Le Bas, Simon Bertie-Roberts, Billy Dilks and colleagues in the Transport and Technical Services, States of Jersey for logistical and technical support with the sampling programme and providing operational data. We are also grateful to: Ian Lamy, Master of States Vessels, the staff of Jersey Harbours and Dave Nuth of Tarka Sea Trips Ltd for assistance with the offshore sampling; John Howard and the staff of Jersey Water for advice and access to the Grands Vaux sampling site; and Anthony Pallot and colleagues from the States of Jersey Meteorological Department for providing rainfall data.