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Department of the Environment

St Aubin’s Bay
Sea Lettuce Literature Review

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EXECUTIVE SUMMARY

Sea lettuce (*Ulva*) is a macroalgae (seaweed) found along all but the most wave exposed coastlines around the world, from tropical to polar climates. *Ulva* species are opportunistic species, capable of very rapid expansion in population size. This leads to the formation of 'green tides', which can lead to serious ecological and economic consequences.

The States of Jersey commissioned Cascade Consulting to undertake a literature review to identify factors controlling the growth of *Ulva* and the conditions which lead to the formation of blooms. Identification of the factors controlling the growth of *Ulva* is crucial for developing an appropriate response to the presence of occasional nuisance levels of sea lettuce in St Aubin's Bay, a large tidal bay on the south coast of Jersey.

Available scientific literature has been reviewed, including consideration of factors controlling growth of *Ulva*. In common with other macroalgae, *Ulva* growth is controlled by a wide range of abiotic and biotic factors, including light, temperature, nutrients, herbivory and competition. The review therefore included detailed discussion of these factors, with particular focus on conditions associated with green tides.

Available light is a key controlling factor in the growth of macroalgae. For this reason the rate of growth of *Ulva* is low during the winter months. When light levels increase in the spring growth remains slow due to low temperatures. The temperature range within which optimum growth can occur will vary across different *Ulva* species. Active growth of *Ulva* generally begins at around 10C with optimum temperatures within 15-20C.

When both light and temperature conditions are favourable the level of nutrients in the water, particularly nitrogen, becomes a key factor for the growth of *Ulva*. The high surface area to volume ratio of *Ulva* species enables a more rapid uptake of nutrients in comparison to other species. For this reason the growth rate of *Ulva* can be very rapid in waters with high levels of nutrients, potentially leading to green tides. Uncertainty surrounds the exact nutrient level required to trigger a bloom but the available evidence suggests it is in the order of 10 millimoles[1] (mmol) per cubic metre (m^3)[2] of dissolved forms of inorganic nitrogen (DIN)[3].

The report also reviewed the nutrient conditions in St Aubin's Bay and compared them to conditions associated with green tides. St Aubin's Bay receives water quality inputs from a number of sources, most notably several streams which drain a large proportion of the island of Jersey and transport nutrients from agricultural land into the Bay. The level of nutrients being transported into St Aubin's Bay via these streams is dependent on both land management practises (such as fertiliser application rates) and rainfall events. The islands main waste water treatment

[1] A mole (mol) is a unit of measurement used in chemistry to express amounts of a chemical substance. A millimole (mmol) represents a thousandth of this unit.
[2] mmol/m^3 is a concentration unit associated with DIN. 1 mmol/m^3 of DIN is equivalent to 0.014mg/l.
[3] DIN is the sum of dissolved ammonia, nitrate and nitrite (3 different forms of nitrogen).

facility, Bellozanne Sewage Treatment Works (STW), also discharges treated effluent into the Bay. In addition the Bay is heavily influenced by water quality in the wider marine oceanic environment. The STW and offshore sources are likely to be relatively constant inputs to the Bay, whereas the land based sources are more variable. Further investigations are required to determine the relative contributions from these sources to the overall nutrient loading in the Bay. Nevertheless, conclusions based on current data indicate that levels of nitrogen in St Aubin's Bay drop below that able to support prolific growth of *Ulva* by mid spring.

The influence of temperature on growth rate means that if seawaters warm up earlier in the spring than usual, this may coincide with high nutrient levels, allowing a proliferation of *Ulva*. The seawater temperature in St Aubin's Bay was warmer than usual in the winters 2006/07 and 2011/12, with the temperatures in January 2007 and 2012 were recorded as 10.2C and 10.0C respectively. A large green tide formed in St Aubin's Bay in both the summer of 2007 and of 2012.

The STW discharge <u>in isolation</u> does not create the algal blooms. Green tides are intermittent and do not occur every year, although the nutrient levels within the discharge are relatively consistent year on year. Should the STW be solely responsible on its own there would be blooms every year. Green tides are therefore triggered by a more complex set of environmental and human-related factors which includes the contribution from the STW. Other environmental conditions/inputs include general climatic conditions and combined nutrient loads from the wider marine sources and a changeable combination of land based derived nutrient loads.

Green tides are an increasing problem in many areas of the world, including Ireland, Kent, France, Portugal and Italy, commonly in bays with a physical resemblance to St Aubin's Bay in terms of tidal movement and adjacent land use. Despite significant resources being allocated to investigating the problem, particularly in France, the most common response to macroalgal blooms in other countries is to simply clear the biomass from beaches and dispose of elsewhere, with the most efficient strategy suggested to be harvesting early in the bloom cycle. This is consistent with the current response to green tides in Jersey, except the biomass is disposed of at low tide. The intermittent nature of macroalgal blooms means that, despite several investigations into potential uses of *Ulva* biomass, creating a market for the removed biomass is problematic.

The impact of a changing climate is likely to be an increasing pressure on bloom formation. Further investigations are needed into specific triggers; however it is clear that temperature plays an important role in the formation of green tides. Increasing seawater temperatures the future means green tides may become more frequent.

More data are required to establish the complex interaction of environmental conditions necessary for an *Ulva* bloom in St Aubin's Bay. Monitoring of the relative load contributions from the wider marine environment, the STW and from other land based runoff towards nutrient conditions in St Aubin's Bay, along with more frequently collected Bay temperature and hydrodynamic data, will enable States of Jersey to better predict the timing of a green tide. This would eventually enable the development of a long term nutrient control strategy, which is ultimately necessary to minimise the occurrence of green tides.

Contents

1 INTRODUCTION

1.1 PURPOSE

This brief review of sea lettuce literature has four aims:

i) investigate the environmental factors which encourage sea lettuce to bloom,

ii) identify the geographical spread of nuisance blooms and similarities to St Aubin's Bay, Jersey,

iii) establish management techniques employed for nuisance blooms,

iv) identify initial conclusions and recommendations.

This literature review is one of a suite of studies investigating the water quality and ecology of the marine environment of St Aubin's Bay. It will assist in the identification of key pressures in the Bay and how to manage them.

1.2 BACKGROUND

Sea lettuce (*Ulva*) is a macroalgae (seaweed) which occurs in coastal environments throughout the world. It is often visible on beaches where it is deposited by the ebb tide. Unlike the majority of macroalgae, sea lettuce can survive once detached from sea bed substrate, allowing the formation of macroalgal blooms, consisting primarily of *Ulva* species. These 'green tides' can result in thick floating mats of algae. The area covered by such mats can be large; the 2008 green tide in the Yellow Sea covered an estimated 3,489km^2, over an area of sea of 84,109km^2 [4].

St Aubin's Bay is a large tidal bay located on the south coast of Jersey which receives water quality inputs from a number of sources, most notably several streams which drain a large proportion of the island of Jersey and the treated effluent from Bellozanne Sewage Treatment Works (STW), the main waste water treatment facility on Jersey. In addition the Bay is heavily influenced by water quality in the wider marine oceanic environment.

Accumulation of algae in St Aubin's Bay has occurred for centuries, and historically this 'vraic' has been harvested for agricultural fertilisers[5]. Vraic is a mixture of drift algae, primarily perennial brown macroalgae such as *Fucus* and *Ascophyllum*, which is washed up from nearby rocky substrate following storm events. These species are not able to survive once detached from the substrate[6]. By contrast green tides are macroalgal blooms, consisting of *Ulva* which can continue to grow once detached. Green tides have been observed in St Aubin's Bay, Jersey since the early 1990s, and to

4 Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.
5 This Is Jersey (2013) *Vraic*, http://www.thisisjersey.com/island-life/history-heritage/vraic/, Accessed 21/08/13
6 Lobban, C.S., Harrison, P.J. (1997) *Seaweed ecology and physiology*, Cambridge University Press

a lesser extent in St Brelade's Bay and Grouville Bay[7]. At times the volume of *Ulva* has become so high the Bay has had the appearance of being 'grassed over'.

Green tides can have serious ecological consequences, changing ecosystem structure and reducing species diversity[8,9,10,11]. Whilst impacts on seagrass are the most widely documented[12,13,14,15,16,17], the anoxic break down of green tides and the attenuation of light levels by the floating mass of algae can impact a range of marine flora and fauna[18,19,20,21,22,23,24] including perennial macroalgae and fish. Ecosystem services such as navigation, fisheries, aquaculture, sailing and tourism can also be impacted, with adverse economic consequences[25]. Release of hydrogen sulphide during the breakdown of large volumes of sea lettuce has also been associated with health issues[26].

The States of Jersey has commissioned Cascade Consulting to undertake a literature review to identify factors controlling the growth of *Ulva* and the conditions which lead to the formation of blooms. The literature review may subsequently inform a review of the management of the sea lettuce in St Aubin's Bay. Identification of the factors controlling the growth of *Ulva* is crucial for developing an appropriate response to the presence of occasional nuisance levels of sea lettuce in St Aubin's Bay.

7States of Jersey (2013) *Beach Seaweed Removal*, TTS Operational Services Directorate Cleaning Services, Technical Briefing Note, 11/07/13.

8 Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K. (1997).Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences, *Limnology and Oceanography* 42, 1105-1118.

9 Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.

10 Guidone, M., Thornber, C.S. (2013) Examination of *Ulva* bloom species richness and relative abundance reveals two cryptically co-occurring bloom species in Narragansett Bay, Rhode Island, *Harmful Algae* 24:1–9.

11 Rogers, P. (2004) Ulva problem in Kent: 1973–2003, *Marine Pollution Bulletin* 49: 145–146.

12 Choi, T.S. Kang, E.J., Kim, J. & Kim, K.Y. (2010) Effect of salinity on growth and nutrient uptake of *Ulva pertusa* (Chlorophyta) from an eelgrass bed, *Algae* 25(1): 17-26.

13 Dolbeth, M., Cardoso, P., Pardal, M.A. (2011) Impact of Eutrophication on the Seagrass Assemblages of the Mondego Estuary (Portugal), In: A.A. Ansari et al. (eds.), *Eutrophication: Causes, Consequences and Control*, Springer Science.

14 Hessing-Lewis, M.L., Hacker, S.D., Menge, B.A., Rumrill, S.S. (2011) Context-Dependent Eelgrass–Macroalgae Interactions Along an Estuarine Gradient in the Pacific Northwest, USA, *Estuaries and Coasts* 34:1169–1181.

15 McGlatherty, K. (2001) Macroalgal blooms contribute to the decline of seagrass in nutrient-enriched coastal waters, *Journal of Phycology* 37:453–456

16 Rasmussen, J.R., Pedersen, M.F., Olesen, B., Nielsen, S.L., Pedersen, T.M. (2013) Temporal and spatial dynamics of ephemeral drift-algae in eelgrass, *Zostera marina*, beds, *Estuarine, Coastal and Shelf Science* 119: 167-175.

17 Thomsen MS, Wernberg T, Engelen AH, Tuya F, Vanderklift MA, et al. (2012) A Meta-Analysis of Seaweed Impacts on Seagrasses: Generalities and Knowledge Gaps, *PLoS ONE* 7(1): e28595. doi:10.1371/journal.pone.0028595.

18 Zhang, J. Huo, Y., Yu, K., Chen, Q., He, Q., Han, W., Chen, L., Cao, J., Shi, D., He, P. (2013) Growth characteristics and reproductive capability of green tide algae in Rudong coast, China, *Journal of Applied Phycology* 25:795–803.

19 Bohórquez, J., Papaspyrou, S., Yúfera, M., van Bergeijk, S.A, García-Robledo, E. Jiménez-Arias, J.L., Bright, M., Corzo, A. (2013) Effects of green macroalgal blooms on the meiofauna community structure in the Bay of Cádiz, *Marine Pollution Bulletin* 70: 10–17.

20 Corzo, A., van Bergeijk, S.A., García-Robledo, E. (2009 Effects of green macroalgal blooms on intertidal sediments: net metabolism and carbon andnitrogen contents, *Marine Ecology Progress Series*. 380: 81–93

21 Dolbeth, M., Cardoso, P.G., Ferreir,a S.M., Verdelhos, T., Raffaelli, D., Pardal, M.A. (2007) Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period, *Marine Pollution Bulletin* 54:576–585.

22 Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.

23Sundbäck, K., Miles, A., Hulth, S., Pihl, L., Engström, P., Selander, E., Svenson, A. (2003 Importance of benthic nutrient regeneration during initiation of macroalgal blooms in shallow bays, *Marine Ecology Progress Series* 246: 115–126.

24 Norkko, A. & Bonsdorff, E. Rapid zoobenthic community responses to accumulations of drifting algae, *Marine Ecology Progress Series* 131: 143–157.

25 Cellina, F., De Leo, G.A., Rizzoli, A.E., Viaroli, P., Bartoli, M. (2003) Economic modelling as a tool to support macroalgal bloom management: a case study (Sacca di Goro, Po river delta) *Oceanologica Acta* 26:139–147.

26 BBC (2009*) Seaweed suspected in French death*, 07/09/09, http://news.bbc.co.uk/1/hi/8242649.stm

1.3 SCOPE OF THE LITERATURE REVIEW

Cascade Consulting has been jointly commissioned by the States of Jersey Department of the Environment and Transport and Technical Services Department to conduct a literature review to establish:

- The geographical distribution of *Ulva* along similar coastlines,
- Environmental factors which encourage *Ulva* to occur in similar geographical areas and how controllable these factors are,
- Environmental factors / thresholds which cause an *Ulva* bloom to occur,
- Review of background nutrient levels and nutrient loading in St Aubin's Bay, including consideration of seasonality,
- How other areas respond to the presence of *Ulva*.

In addition to local information provided by the States of Jersey Department of the Environment, the literature review process included a search of the relevant scientific literature (using the Web of Knowledge). Initial search terms for this review were:

- *Ulva* (9780 search results)
- 'growth rate' & *Ulva* (321 search results)

These terms were refined to filter the results and provide a list of abstracts to assess for relevance:

- 'algal bloom' & *Ulva* (53 search results)
- 'macroalgae bloom' & *Ulva* (34 search results)
- 'growth rate' & *Ulva* & bloom (25 search results)
- nitrate or nitrogen & *Ulva* (246 search results)

In addition, an internet search of unpublished reports and grey literature was conducted using the same search terms. All search result abstracts were viewed and a decision was made as to whether the document was relevant to this review. If the document was relevant it was downloaded and read. This search yielded 105 articles of relevance to the current study. The most relevant were prioritised for reading. In total 79 articles were read and summarised, with a further 26 articles downloaded but not read due to time constraints. Key information was entered into an electronic reference database with use of key words to facilitate future searches. This database includes the abstract of each article and has been provided on a CD accompanying this report.

Priority was given to studies which had been conducted in similar geographical areas to Jersey, however the review was constrained by the scientific literature available. No studies on *Ulva* were available for other bays in Jersey.

2 GROWTH AND DISTRIBUTION OF *ULVA*

2.1 GEOGRAPHICAL DISTRIBUTION & SPECIES IDENTIFICATION

Species belonging to the genus *Ulva* are common worldwide from tropical to polar climates[27], and are also found on all but the most exposed shores throughout Europe[28]. Species with a tubular form until recently were considered to belong to a separate genus *Entermorpha* however phylogenic studies now place them in the same genus[29]. This means the genus now consists of over 90 species[30].

Expert identification is required to separate the species, as many only differ on a microscopic level, so identification to species level is not possible on the basis of morphology alone[31]. Green tides may also be comprised of more than one species. For these reasons the exact species composition of green tides is often unknown. This review has therefore encompassed all *Ulva* species.

2.2 ENVIRONMENTAL FACTORS CONTROLLING GROWTH

Ulva species are usually the first colonisers on open substrata, and their cosmopolitan presence is attributed to their tolerance of a wide range of environments and opportunistic life strategy. In common with other macroalgae, growth is controlled by a wide range of abiotic and biotic factors, including light, temperature, nutrients, herbivory and competition[32]. A summary of the literature review findings regarding *Ulva* growth is summarised in Table 2.1. This illustrates the complex interactions between environmental variables that are necessary for optimal growth. Each factor is then discussed in more detail, followed by a discussion of the role biotic factors may play in controlling *Ulva* growth.

27 Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Jensen, P.D. (2011) Bioenergy potential of *Ulva lactuca*: Biomass yield, methane production and combustion, *Bioresource Technology* 102: 2595–2604.
28 Paolo Pizzolla 2008. *Ulva lactuca*. Sea lettuce. Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme [on-line]. Plymouth: Marine Biological Association of the United Kingdom. Available from: <http://www.marlin.ac.uk/speciesinformation.php?speciesID=4541>
29 Hayden, H.S., Blomster, J., Maggs, C.A., Silva, P.C., Stanhope, M.J. & Waaland, J.R. (2003). Linnaeus was right all along: Ulva and Enteromorpha are not distinct genera. *European Journal of Phycology* 38: 277-294.
30 Guiry, M.D. & Guiry, G.M.(2013) *AlgaeBase*. World-wide electronic publication, National University of Ireland, Galway. http://www.algaebase.org; searched on 18 August 2013.
31 Guidone, M., Thornber, C.S. (2013) Examination of *Ulva* bloom species richness and relative abundance reveals two cryptically co-occurring bloom species in Narragansett Bay, Rhode Island, *Harmful Algae* 24:1–9.
32 Loban & Harrison (1994) *Seaweed Ecology and Physiology*, Cambridge University Press

Table 2.1 Effect of abiotic factors on growth of *Ulva* species: Summary of findings

Study	Geographic area	Species	Temperature	Nutrients	Salinity	pH
Taylor *et al.* 2001	Langstone Harbour, UK	*U. curvata* & *U.rigida*	optimal growth at 15C			
Bruhn *et al.* 2011	Denmark	*U. lactuca*	growth decreased over 20C			
Geertz-Hanse & Sand-Jensen 1992	Denmark	*U. lactuca*		strong correlation between total N and chla content		
Berglund 1969 (in Kessing *et al.* 2011)	Sweden	*U. linza*		14mmol/m³ DIN optimal		
Malta & Verchuure 1997	Netherlands	*Ulva* spp.		DIN only variable to explain any variation in growth rates	growth not correlated with salinity in lagoon	
Lotze & Schramm 2000	Schlei Fjord, Germany			nitrate far greater effect on growth than phosphate		
Viaroli *et al.* 2005	Po River, Italy	*U. rigida*	growth initiated at 10-12C in March			
Cellina *et al.* 2003	Po River, Italy	*U. rigida*	max growth at 15C			
Kalita & Titlyanov 2013	Amursky Bay, Russia	*U. lactuca*	15-20C reproductive growth, only vegetative at 5-10C			
Teichberg *et al.* 2010	Europe, North & South America	*U. lactuca*		growth shows log relationship with DIN, but response to enrichment decreases with ambient [N]		
Fry *et al.* 2013	Hutt River, NZ	*U. intestinalis*		bloom at: DIN 10-25mmol/m³ & SRP 0.1-0.5 mmol/m³	growing at sites within estuary ramging 0-34 ppm	
Guidone *et al.* 2012	Rhode Island, US	*U.compressa* & *U.rigida*	growth at 19-21C			
Li *et al.* 2009 (in Kessing *et al.* 2011)	Yellow Sea, China	*U. prolifera*		biomass addition of 6% per day at 10mmol/m³ DIN		
Kessing *et al.* 2011	Yellow Sea, China	*U. prolifera*	optimal growth at 15-20C			
Lin *et al.* 2011	Yellow Sea, China	*U. prolifera*			higher salinities better for reproductive growth	growth highest at pH7
Liu, D. *et al.* 2013	Yellow Sea, China	*U. prolifera*		optimal growth at 50 mmol/m³ DIN but grows well at 500 mmol/m³		
Luo *et al.* 2012	Yellow Sea, China	*U. prolifera* & *U. linza*	15-20C optimal for growth	growth high 20mmol/m³ and 200 mmol/m³ nitrate		
Dailer *et al.* 2012	Hawaii	*U. lactuca*		growth increased with addition of 4.3mmol/m³ nitrate, supressed at 0.05 mmol/m³ nitrate		
Hodges unpubl. (in Lapointe 1997)	Hawaii	*U. fasciata*		blooms reported at DIN 4.70mmol/m³ & SRP 0.29 mmol/m³		
Laponte 1997	Florida & Caribbean	*U. fasciata*		bloom at DIN 1 mmol/m³ & SRP 0.1 mmol/m³		

2.2.1 Light

In common with other opportunistic algal species *Ulva* species are highly efficient at capturing available light resources[33],[34]. The thin (2-cells thick) blade morphology ensures all cells are exposed to ambient radiation. This efficiency is particularly pronounced in low light conditions[35] where the light capturing apparatus is modified to ensure maximum transfer of energy through the photosynthetic process into carbon production[36],[37]. Despite this efficiency there are periods of the year, particularly in temperate regions, in which light levels are not adequate for growth.

Macroalgae are capable of photoaccilimation, meaning a species will adjust its light harvesting apparatus to remain most efficient in a particular light environment[38]. This ability has been demonstrated in *Ulva*[39],[40] and for this reason it is not possible to specify exact light thresholds for growth in St Aubin's Bay from other studies, however it is known that the photosynthetic rate is likely to be saturated at around 100 *u*mol.m^{-2}.s^{-1} [41].

The profound influence available light has on the growth of all macroalgal species leads to a distinct seasonal pattern in growth peaking in summer. Regardless of the other factors controlling growth discussed below, if light resources are not sufficient to support growth then biomass will remain low.

2.2.2 Temperature

Temperature controls the rate of a myriad of reactions within the macroalgal thallus, in particular those related to photosynthesis and biomass production. All *Ulva* species will grow only within a set range of temperatures, and thus temperature also exerts an influence on the seasonal pattern of growth.

Numerous studies have either directly or indirectly investigated the temperature range in which *Ulva*species grow in temperate regions[42],[43],[44],[45],[46]. These studies show

33 Xu, J., Gao, K. (2012) Future CO2-Induced Ocean Acidification Mediates the Physiological Performance of a Green Tide Alga, *Plant Physiology* 160:1762–1769.
34 Luo, M.B., Liu, F., Xu, Z.L. (2012) Growth and nutrient uptake capacity of two co-occurring species, *Ulva prolifera* and *Ulva linza* Aquatic Botany 100 (2012) 18– 24.
35 Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.
36 Lobban, C.S., Harrison, P.J. (1997) *Seaweed ecology and physiology*, Cambridge University Press.
37 Geertz-Hansen, O., Sand-Jensen, K. (1992) Growth rates and photon yield of growth in natural populations of a marine macroalga *Ulva lactuca*, *Marine Ecology Progress Series* 81:179-183.
38 Falkowski PG, La Roche J (1991) Acclmation to spectral irradiance in algae, *Journal of Phycology* 27:8-14.
39 Henley, W.J., Ramus, J. (1989) Optimization of pigment content and the limits of photoacclimation for *Ulva rotundata* (Chlorophyta), *Marine Biology* 103:267-274.
40 Vergara, J.J., Pérez-Lloréns, J.L., Peralta, G., Hernández, I., and Niell, F.X. (1997) Seasonal variation of photosynthetic performance and light attenuation in *Ulva* canopies from Palmones river estuary, *Journal of Phycology* 33: 773-779.
41 Luo, M.B., Liu, F., Xu, Z.L. (2012) Growth and nutrient uptake capacity of two co-occurring species, *Ulva prolifera* and *Ulva linza, Aquatic Botany* 100 (2012) 18– 24.
42 Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Jensen, P.D. (2011) Bioenergy potential of *Ulva lactuca*: Biomass yield, methane production and combustion, *Bioresource Technology* 102: 2595–2604.
43 Guidone, M., Thornber, C.S., Vincent, E. (2012) Snail grazing facilitates growth of two morphologically similar bloom-forming *Ulva* species through different mechanisms, *Journal of Ecology*, 100: 1105–1112.
44 Kalita, T.L., Titlyanov, E.A. (2013) Influence of temperature on the infradian growth rhythm in *Ulva lactuca* (Chlorophyta), *European Journal of Phycology*, 48:210-220

remarkable agreement, despite the range of *Ulva* species investigated, and point to an optimum temperature range of 15-20C for growth (see **Table 2.1**). Active growth also occurs at lower temperatures. Growth initiation in an Italian estuary, for example, was reported to occur in March when temperatures were in the range 10-12C[47]. However, addition to biomass is unlikely to be significant below the optimum temperature range.

Temperature has also been shown to influence the reproductive state of *Ulva*. At low temperatures (5-10C) *U. lactuca* remains in a vegetative state, only switching to a reproductive state at 15-20C[48]. *Ulva* has a rapid growth rate, which means a population can increase extremely quickly. The daily growth rate of green tide algae in the Yellow Sea (*U. porifera*) reached a maximum of 56.2%, meaning the biomass could double in two days[49]. However, the reproductive capacity of this species was also found to be large- the estimations indicated that 1g (fresh weight) of blades was able to produce about 2.8×10^{8}– 2.7×10^{9} new younger seedlings. This indicates that reproduction can also become a key factor in expansion of the green tide at certain temperatures.

2.2.3 Nutrients

Light availability and temperature are not generally features of the marine environment which are directly altered through anthropogenic activities. Power generation may alter water temperature over a small area and increased suspended solids can also reduce light availability for marine plants and algae. Nutrient levels of coastal waters however are far more likely to be affected by human intervention. The eutrophication of coastal waters represents one of the most damaging anthropogenic influences in the coastal zone. Most cases of algal blooms- both microalgal and macroalgal- are associated with elevated nutrient levels[50,51,52].

Increases in nutrient supply can alter the physiology of macroalgae. The high surface area to volume ratio of *Ulva* enables rapid uptake of nutrients. The ambient nutrient regime has been shown to also influence the uptake ability of *Ulva*. The nutrient uptake rate and the photosynthetic efficiency of *U. lactuca* increases in response to

45 Luo, M.B., Liu, F., Xu, Z.L. (2012) Growth and nutrient uptake capacity of two co-occurring species, *Ulva prolifera* and *Ulva linza Aquatic Botany* 100 (2012) 18– 24.
46 Viaroli, P., Bartoli, M. Azzoni, R., Giordani, G., Mucchino, C., Naldi, M., Nizzoli, D., Taje, L. (2005) Nutrient and iron limitation to *Ulva* blooms in a eutrophic coastal lagoon (Sacca di Goro, Italy), *Hydrobiologia* 550:57–71
47 Viaroli, P., Bartoli, M. Azzoni, R., Giordani, G., Mucchino, C., Naldi, M., Nizzoli, D., Taje, L. (2005) Nutrient and iron limitation to *Ulva* blooms in a eutrophic coastal lagoon (Sacca di Goro, Italy), *Hydrobiologia* 550:57–71
48 Kalita, T.L., Titlyanov, E.A. (2013) Influence of temperature on the infradian growth rhythm in *Ulva lactuca* (Chlorophyta), *European Journal of Phycology*, 48:210-220
49 Zhang, J. Huo, Y., Yu, K., Chen, Q., He, Q., Han, W., Chen, L., Cao, J., Shi, D., He, P. (2013) Growth characteristics and reproductive capability of green tide algae in Rudong coast, China, *Journal of Applied Phycology* 25:795–803.
50 Rogers, P.J., Dake, N., Dussart G.B.J. (2004) *Ulva* problem in Kent: 1973–2003 *Marine Pollution Bulletin* 49: 145–146.
51 Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K. (1997).Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences, *Limnology and Oceanography* 42, 1105-1118.
52Zhang, J. Huo, Y., Yu, K., Chen, Q., He, Q., Han, W., Chen, L., Cao, J., Shi, D., He, P. (2013) Growth characteristics and reproductive capability of green tide algae in Rudong coast, China, *Journal of Applied Phycology* 25:795–803.

increased nutrient supplies[53]. This makes the alga highly capable of rapid expansion in growth in high nutrient conditions, compared to low nutrient conditions[54].

Ulva also has the ability to engage in 'luxury consumption' of nutrients at nutrient concentrations beyond which productivity rates are saturated[55,56,57]. This enables the alga to store nutrients for use when levels are lowered, thereby maintaining high growth rates for up to several weeks following a reduction in nutrient supply. Nitrate is stored in vacuoles, the capacity to store other nutrients is more limited.

The nutrient dynamics in coastal environments means algae tend to be nitrogen limited rather than phosphorus limited[58], thus elevated levels of nitrogen are most likely to result in a disturbance to the system[59,60]. Many studies have confirmed the role nitrogen plays in the formation of green tides[61,62]. The form of nitrogen most available tends to be nitrate, although *Ulva* will preferentially take up ammonia if available as it is less energetically costly[63]. Nitrogen has been reported as limiting the growth of *Ulva* in numerous studies[64,65,66,67]. Mitigation measures targeting nitrogen levels have also been successful in reducing the appearance of green tides[68], lending further support to the conclusion nitrogen is a key controlling factor in green tide production.

Due to their lower demands for nutrients, slow growing, perennial macroalgae (e.g. *Fucus*) are better adapted to flourish in low nutrient conditions than fast growing

53 Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.
54 Pérez-Mayorga, D.M., Zertuche-González , J.A., Leichter, J.J., Filonov, A.E. Lavín, M.F. (2011) Nitrogen uptake and growth by the opportunistic macroalga *Ulva lactuca* (Linnaeus) during the internal tide, *Journal of Experimental Marine Biology and Ecology* 406: 108–115.
55 Buapet, P., Hiranpan, R., Ritchie, J., Prathep, A. (2008) Effect of nutrient inputs on growth, chlorophyll, and tissue nutrient concentration of *Ulva reticulata* from a tropical habitat, *ScienceAsia* 34 (2008): 245–252.
56 Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.
57 Pedersen, M.F., Borum, J. (2006) Nutrient control of algal growth in estuarine waters. Nutrient limitation and the importance of nitrogen requirements and nitrogen storage among phytoplankton and species of macroalgae, *Marine Ecology Progress Series*, 142: 261-272.
58 Howarth, R.W., Marino, R. (2006) Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over three decades, *Limnology & Oceanography*., 51:364–376.
59 Briand, X., Morand, P. (1997) Anaerobic digestion of *Ulva* sp. 1. Relationship between *Ulva* composition and methanisation, *Journal of Applied Phycology* 9: 511–524.
60 Teichberg, M., Fox, S.E., Olsen, Y.S., Valiela, I., Martinetto, P., Iribarne, O., Muto, E.Y., Petti, M.A.V., Corbisier, T.N., Soto-Jimenez, M., Paez-Osuna, F., Castro, P., Freitas, H., Zitelli, A., Cardinaletti, M., and Tagliapietra, D. (2010) Eutrophication and macroalgal blooms in temperate and tropical coastal waters: Nutrient experiments with *Ulva* spp., *Global Change Biology* 16: 2624-2637.
61 Merceron, M., Antoine, V., Auby, I., Morand, P. (2007) In situ growth potential of the subtidal part of green tide forming *Ulva* spp. stocks, *Science of The Total Environment* 384: 293-305, & references therein.
62 Ménesguen, A., Piriou, J-Y., (1995) Nitrogen loadings and macroalgal (*Ulva* sp.) Mass Accumulation in Brittany (France), *Ophelia* 42:227-237.
63 Lotze, H.K., Schramm, W. (2000) Ecophysiological traits explain species dominance patterns in macroalgal blooms, *Journal of Phycology* 36:287–295.
64 Lotze, H.K., Schramm, W. (2000) Ecophysiological traits explain species dominance patterns in macroalgal blooms, *Journal of Phycology* 36:287–295.
65 Malta, E., Verschuure, J.M. (1997) Effects of environmental variables on between-year variation of *Ulva* growth and biomass in a eutrophic brackish lake, *Journal of Sea Research* 38: 71-84.
66 Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.
67 Li et al (2009) in Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.
68 Dolbeth, M., Cardoso, P.G., Ferreir,a S.M., Verdelhos, T., Raffaelli, D., Pardal, M.A. (2007) Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period, *Marine Pollution Bulletin* 54:576–585.

opportunistic species[69] such as *Ulva* . This means that rapid growth of opportunistic species in the spring when light levels increase is normally balanced by the prolonged growth of perennials and the system balance is maintained. However, in nutrient rich waters the growth of opportunists is prolonged, leading to the excessive growth characterised by green tides. This nutrient influx must occur at a time in which light and temperature conditions are adequate for growth. A study of *Ulva* growth in Brittany found the nitrogen loadings must occur in June for green tides to form[70]. The nutrient threshold above which the system becomes unbalanced is therefore a key factor in the formation of nuisance levels of *Ulva*.

Reported levels of nitrogen at which *Ulva* proliferation is triggered vary widely. In tropical systems 1mmol/m^3 dissolved inorganic nitrogen (DIN) and 0.1 mmol/m^3 soluble reactive phosphorus (SRP) are suggested as the threshold for algal bloom conditions[71]. However, elsewhere in the tropics the values have been set at 4.7mmol/m^3 DIN and 0.29mmol/m^3 SRP[72] and the suppression of growth was reported to occur at 0.05mmol/m^3 DIN. In colder climates more comparable to Jersey, nutrient threshold values for elevated growth are higher, varying from 10mmol/m^3 [73]-50mmol/m^3 [74] DIN (see **Table 2.1**). The level at which growth of *Ulva* is supressed is very high, *U. prolifera* is reported as growing well at concentrations as high as 500 mmol/m^3 DIN.

Nutrients stored in benthic sediment may also act as a source of for macroalgal growth, complicating efforts to understand the mechanisms behind green tides. A study in a shallow, sheltered bay in Sweden estimated that benthic efflux of inorganic nutrients could supply up to 55 to 100% of the estimated nitrogen demand and 30 to 70% of the phosphorus requirements for the initial macroalgal growth from May to June[75]. A similar scenario of decaying algal biomass and the subsequent efflux of nutrients from sediment in supporting *Ulva* growth and development of blooms has also been reported elsewhere[76].

2.2.4 Salinity & pH

The large focus on the role nutrients play in *Ulva* growth means the literature is sparse on other topics. Nevertheless, some limited information is available.

69 Martínez, B., Pato, L.S., Rico, J.S. (2012) Nutrient uptake and growth responses of three intertidal macroalgae with perennial, opportunistic and summer-annual strategies, *Aquatic Botany* 96:14– 22.
70 Ménesguen, A., Piriou, J-Y., (1995) Nitrogen loadings and macroalgal (*Ulva* sp.) Mass Accumulation in Brittany (France), *Ophelia* 42:227-237.
71 Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.
72 Hodges (unpublished) in Lapointe, B.E. (1997) Nutrient Thresholds for Bottom-Up Control of Macroalgal Blooms on Coral Reefs in Jamaica and Southeast Florida, *Limnology and Oceanography* 42:1119-1131.
73 Fry, B., Rogers, K., Barry, B., Barr, N., Dudley, B. (2011) Eutrophication indicators in the Hutt River Estuary, New Zealand, *New Zealand Journal of Marine and Freshwater Research*, 45: 665-677.
74 Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.
75 Sundbäck, K., Miles, A., Hulth, S., Pihl, L., Engström, P., Selander, E., Svenson, A. (2003) Importance of benthic nutrient regeneration during initiation of macroalgal blooms in shallow bays, *Marine Ecology Progress Series* 246: 115–126.
76 García-Robledo, E., Revsbech, N.P. Risgaard-Petersen, N. Corzo, A. (2013) Changes in N cycling induced by *Ulva* detritus enrichment of sediments, *Aquatic Microbial Ecology* 69: 113–122.

Ulva species tend to have broad salinity tolerances, growing in almost freshwater systems to fully marine environments. Recent studies in China on the causes of the Yellow Sea green tides have included an investigation of the effect of salinity on *U. prolifera*. The findings point to important salinity controls on reproductive status of the algae. Higher salinities were found to be better for reproductive growth[77]. The changes in freshwater flow into the Yellow Sea following the completion of the Three Gorges Dam (now occurring primarily January-May) may in part have resulted in the large green tides in the Yellow Sea.

Generally pH in the marine environment remains relatively constant, at around 7.5-8.5. It is therefore not an environmental factor that is likely to vary enough to have a major control over the growth of *Ulva*. Nevertheless, large variations and influxes of water from the land are one mechanism by which the pH of coastal waters may be altered.

Some evidence points to the reproductive status of *U. prolifera* being influenced by pH levels, with cells remaining vegetative at low pH[78]. The retention of water in the Three Gorges Dam creates a dry period in the Yellow Sea, reducing the once significant dilution effect of the Yangtze River. The pH (and salinity) of the coastal waters increases, triggering formation of reproductive cells. Once freshwater flows increase, bringing an influx of nutrients, the population is able to rapidly expand, potentially leading to a green tide. The influence of pH and salinity may not be as important as other water quality parameters in bloom formation, but this research indicates that in particular situations these factors could be more influential.

2.2.5 Water Motion

Ulva has been recorded as growing in wide variety of environments, ranging from low energy estuaries to high energy rocky shores[79]. Conditions which favour the proliferation of *Ulva* growth, however, are reported as environments with low wave motion. For this reason it has generally been assumed that sites that favour green tides have certain characteristics such as wide foreshores exposed at low tide and weak residual currents[80]. However, recent observations of a green tide in New Zealand suggest that wave action does not suppress the growth of *U. intestinalis*[81].

Due to the broad range of conditions that *Ulva* is capable of growing in it is not possible to provide exact thresholds for growth, but low energy, sheltered

77 Lin, A.P., Wang, C., Pan, G-H, Song, L, Gao, S., Xie, X., Wang, Z., Niu, J., Wang, G. (2011) Diluted seawater promoted the green tide of *Ulva prolifera* (Chlorophyta, Ulvales), Phycological Research 2011; 59: 295–304.
78 Lin, A.P., Wang, C., Pan, G-H, Song, L, Gao, S., Xie, X., Wang, Z., Niu, J., Wang, G. (2011) Diluted seawater promoted the green tide of *Ulva prolifera* (Chlorophyta, Ulvales), Phycological Research 2011; 59: 295–304.
79 Paolo Pizzolla 2008. *Ulva lactuca*. Sea lettuce. Marine Life Information Network: Biology and Sensitivity Key Information Sub-programme [on-line]. Plymouth: Marine Biological Association of the United Kingdom. Available from: http://www.marlin.ac.uk/speciesinformation.php?speciesID=4541.
80 Merceron, M., Antoine, V., Auby, I., Morand, P. (2007) *In situ* growth potential of the subtidal part of green tide forming *Ulva* spp. stocks, *Science of The Total Environment* 384: 293-305.
81 Fry, B., Rogers, K., Barry, B., Barr, N., Dudley, B. (2011) Eutrophication indicators in the Hutt River Estuary, New Zealand, *New Zealand Journal of Marine and Freshwater Research*, 45: 665-677.

environments with a broad foreshore, such as that found in St Aubin's Bay do appear to favour the formation of green tides. It is likely that the low velocity environment contributes to lower dilution of nutrients and increased residence time in these waterbodies, which may have more control on the growth of *Ulva* than the level of water movement itself.

Water motion does have a crucial role in moving the bulk of the green tide towards the higher shoreline, where is becomes a problem for beach users. In St Aubin's Bay the green tide anecdotally occurs on the beach only at spring tides. In this context, hydrodynamics do not increase the volume of biomass in the green tide, but it is an important factor in turning the green tide into a problem.

2.2.6 Biotic Factors

Control of macroalgal population size through abiotic factors is known as 'bottom up' control. There is also evidence for 'top down' control of growth of *Ulva* via biotic factors such as competition and herbivory.

The timing of germination of overwintering spores in early spring, and grazing of spores and germlings (the early sessile developmental stage which develops into larger, mature blades) by mesograzers in late spring and summer, may be important processes controlling the initiation of annual macroalgal blooms and species dominance patterns within these blooms[82]. The number of grazers (snails) required for control of germlings is low, however many are needed for the control of mature blades.

Herbivores may also facilitate green tides by grazing on the epiphytic growth on *Ulva* blades or by providing nitrogenous waste inputs[83].

The existence of a seed biomass is an important prerequisite for algal blooms[84]. Studies of the causes of the Yellow Sea green tides have been focused on the role aquaculture rafts and nearby sand banks played in providing habitat for *U. prolifera* spores and filaments[85],[86],[87]. Other studies indicate that benthic invertebrates can provide substrate for spores and filaments, which contributes to the rapid expansion

82 Lotze, H. K., Schramm, W., Schories, D. and Worm, B. (1999) Control of macroalgal blooms at early developmental stages: *Pilayella littoralis* versus *Enteromorpha* spp., *Oecologia* 119: 46-54.
83 Guidone, M., Thornber, C.S., Vincent, E. (2012) Snail grazing facilitates growth of two morphologically similar bloom-forming *Ulva* species through different mechanisms, *Journal of Ecology*, 100: 1105–1112
84 Keesing, J.K., Liu, D., Fearns, P., Garcia, R., 2011. Inter- and intra-annual patterns of *Ulva prolifera* green tides in the Yellow Sea during 2007e2009, their origin and relationship to the expansion of coastal seaweed aquaculture in China, *Marine Pollution Bulletin* 62, 1169-1182.
85 Pang, S.J., Liu, F., Shan, T.F., Xu, N., Zhang, Z.H., Gao, S.Q., Chopin, T., Sun, S. (2010) Tracking the algal origin of the Ulva bloom in the Yellow Sea by a combination of molecular, morphological and physiological analyses, *Marine Environmental Research* 69: 207-215.
86 Liu, D., Keesing, J.K., Dong, Z., Zhen, Y., Di, B., Shi, Y., Fearns, P., Shi, P. (2010) Recurrence of Yellow Sea green tide in June 2009 confirms coastal seaweed aquaculture provides nursery for generation of macroalgal blooms, *Marine Pollution Bulletin* 60, 1423–1432.
87 Liu, D., Keesing, J.K., Xing, Q., Shi, P. (2009) The world largest green-tide caused by *Porphyra* aquaculture, *Marine Pollution Bulletin* 58: 888–895.

of *Ulva* in springtime[88].

2.3 BLOOM COLLAPSE

In the absence of nutrient limitation, the mechanisms involved in termination or collapses of macroalgal blooms are not well understood[89]. Several mechanisms are likely to be responsible for ending a macroalgal bloom, such as grazing, nitrate toxicity and physiological responses. One explanation is that increasing nutrient supply stimulates phytoplankton growth and this in turn increases shading of the macroalgae below, slowing growth rates. The collapse of *Ulva* blooms is reported to occur when biomass densities exceed levels around 200-900gDW.m^{-2} and an 'anoxic crisis' results, reducing available oxygen to algal tissue to a level below which *Ulva* can survive[90].

In some cases the bloom cessation will be related to a reduction in the levels of nutrients available to a level below the threshold for prolific growth[91]. This will lead to a subsequent reduction in the rate of growth.

Dramatic changes in environmental conditions may also break green tides. A green tide in the Yellow Sea collapsed following the arrival of typhoons which caused temperatures and rainfall levels to rapidly increase[92].

88 Pihl, L., Magnusson, G., Isaksson, I., Wallentinus, I. (1996) Distribution and growth dynamics of ephemeral macroalgae in shallow bays on the Swedish west coast, *Journal of Sea Research*, 35: 169-180
89 Valiela, I., McClelland, J., Hauxwell, J., Behr, P.J., Hersh, D., Foreman, K. (1997).Macroalgal blooms in shallow estuaries: controls and ecophysiological and ecosystem consequences, *Limnology and Oceanography* 42, 1105-1118.
90 Cellina, F., De Leo, G.A., Rizzoli, A.E., Viaroli, P., Bartoli, M. (2003) Economic modelling as a tool to support macroalgal bloom management: a case study (Sacca di Goro, Po river delta), *Oceanologica Acta* 26:139–147
91 Dailer, M.L., Smith, J.E., Smith, C.M. (2012) Responses of bloom forming and non-bloom forming macroalgae to nutrient enrichment in Hawai'i, USA, *Harmful Algae* 17:111–125.
92 Wang, Y., Wang, Y., Zhu, L., Zhou, B., Tang, X. (2012) Comparative Studies on the Ecophysiological Differences of Two Green Tide Macroalgae under Controlled Laboratory Conditions. *PLoS ONE* 7(8): e38245. doi:10.1371/journal.pone.0038245.

3 ST AUBIN'S BAY NUTRIENT REVIEW

A range of studies have previously been undertaken to assess water quality and the potential for ecological impacts in St Aubin's Bay. The results of these studies[93,94] are summarised below, with particular attention given to nitrogen, given the role nutrient that supply plays in *Ulva* growth, as identified in Section 2.

3.1 BACKGROUND NUTRIENT LEVELS

Marine water quality sampling was undertaken along a 40km transect stretching approximately southwards from St Aubin's Bay[95]. Sampling occurred on 18 March 2013. The location of sampling points is indicated in **Figure 3.1**.

Figure 3.1 Map of offshore marine quality monitoring sites

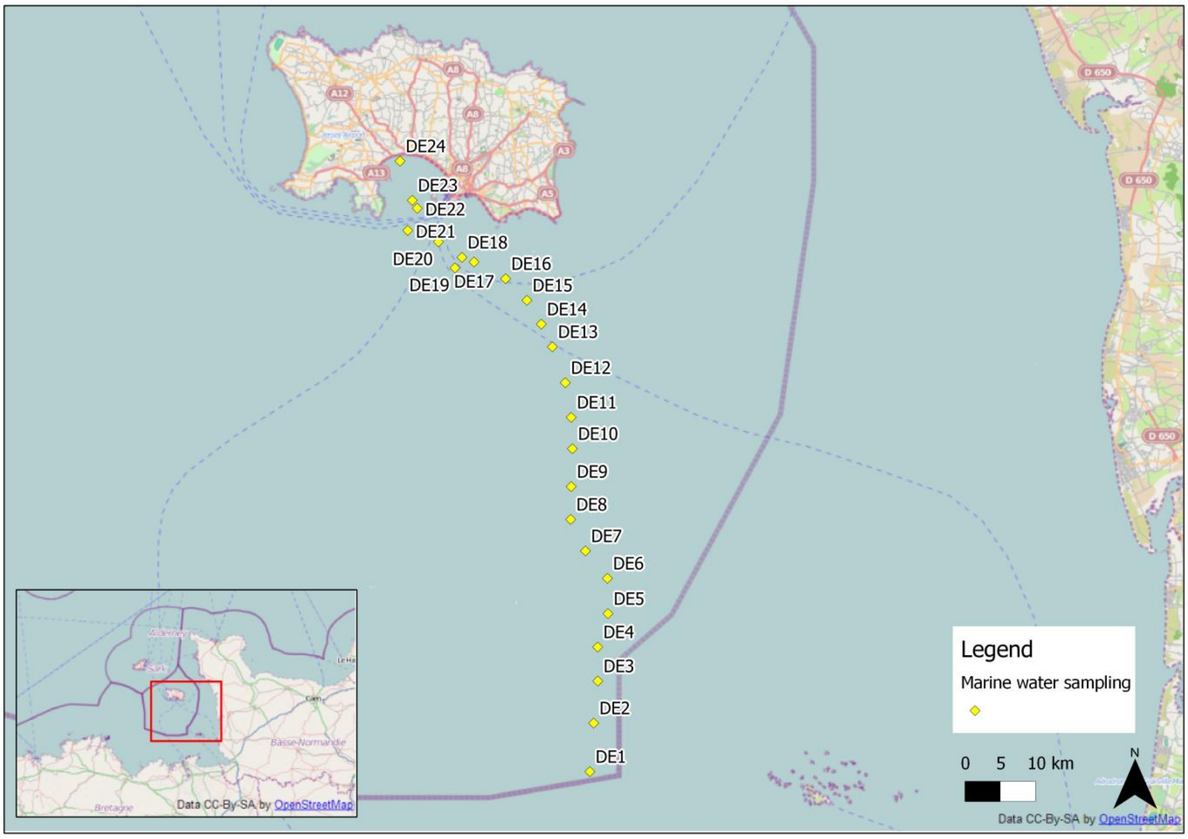


Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

The sampling was undertaken to determine the offshore water quality conditions and compare them to nearshore conditions. Plots of selected determinands against distance from the first site in St Aubin's Bay are shown in **Figures 3.2 and 3.3**.

93 Cascade Consulting (2013) *St Aubin's Bay Winter and Spring 2013 Water Quality Monitoring Report*, Report to States of Jersey, TTS.
94 Cascade Consulting (2013) *Review of available historic freshwater and marine data from St Aubin's Bay and surrounding areas*, Report to States of Jersey, TTS.
95 Cascade Consulting (2013) *Review of available historic freshwater and marine data from St Aubin's Bay and surrounding areas*, Report to States of Jersey, TTS

Figure 3.2 Dissolved inorganic nitrogen concentration with distance from the first monitoring site in St Aubin's Bay

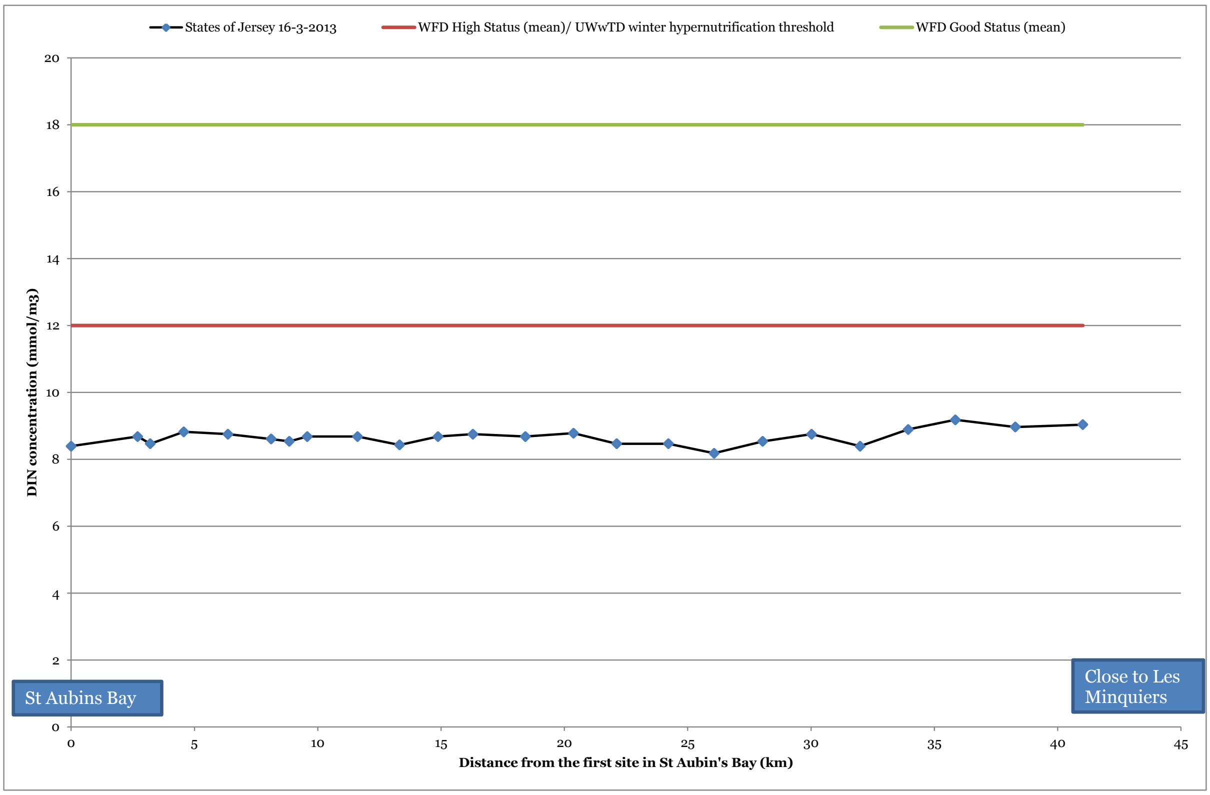


Figure 3.2 shows that dissolved inorganic nitrogen (DIN) levels along the transect are relatively constant, remaining between 8-9 mmol/m3. Transitional and Coastal (TRAC) waterbody WFD DIN thresholds are shown for information. These levels are adequate for healthy growth of *Ulva* but remain just below the level associated elsewhere with prolific growth.

Figure 3.3 Soluble reactive phosphorus concentration with distance from the first monitoring site in St Aubin's Bay

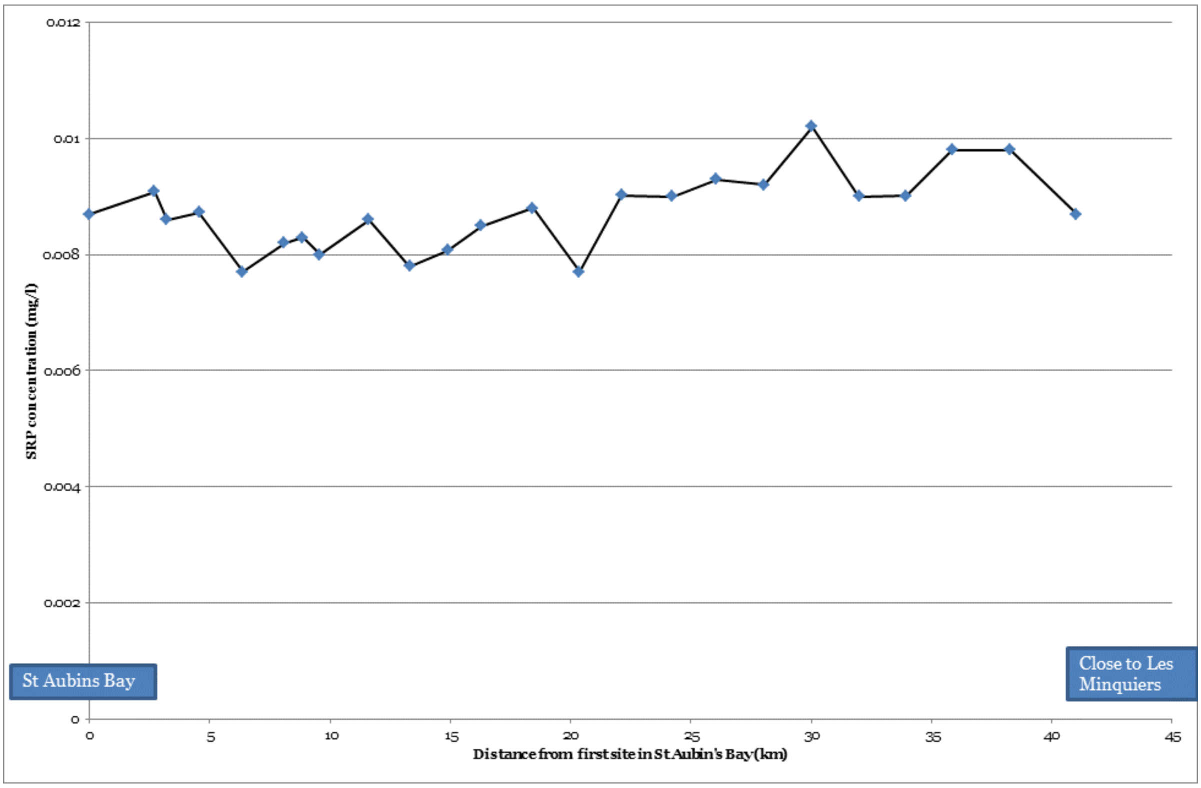


Figure 3.3 shows soluble reactive phosphorus (SRP) levels along the transect are steady. Together with **Figure 3.2**, this shows that nutrient levels do not vary significantly along the transect.

The results indicate that, at the end of winter, concentrations of nutrients in St Aubin's Bay are similar to those significantly further offshore. Nutrient levels are therefore consistent with background marine concentrations. From the evidence available the phosphorus and nitrogen concentrations in the Bay are not considered to be highly elevated. In the absence of a large competitive advantage over slower growing perennial macroalage, such as high nutrient concentrations, *Ulva* cannot expand to bloom proportions. The evidence so far indicates that the background level provided by the wider marine environment in combination with the relatively constant source from Bellozanne STW, does not provide enough nutrients to provide this competitive advantage.

3.2 WINTER & SPRING MONITORING IN ST AUBIN'S BAY

Detailed monitoring was undertaken in winter and spring 2013[96] in order to further understand the water quality of the streams entering St Aubin's Bay and the water quality of the Bay itself.

96 Cascade Consulting (2013) *St Aubin's Bay Winter and Spring 2013 Water Quality Monitoring Report*, Report to States of Jersey, TTS.

The winter and spring monitoring consisted of spot water quality sampling over an eight week period in January to February 2013 and April to May 2013 in the seven main streams flowing into St Aubin's Bay, namely; St Brelade's Stream, La Haule A, La Haule B, Sandybrook, Waterworks Valley Stream, Upstream (of Bellozanne) STW and Weighbridge Stream (**Figure 3.4**) and also at seven sites within the bay along a transect (**Figure 3.5**). In addition, water quality following a rainfall event in March 2013 was recorded via the automated sampling of water from four of the seven streams flowing into St Aubin's Bay.

Figure 3.4 Stream water quality spot sampling locations

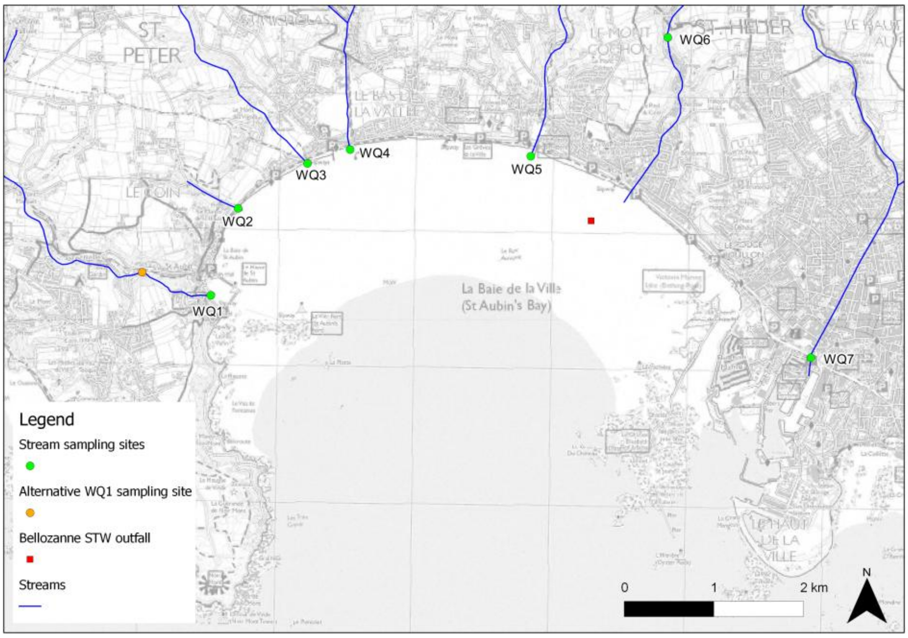


Figure base map supplied by States of Jersey.

Figure 3.5 Marine sampling locations

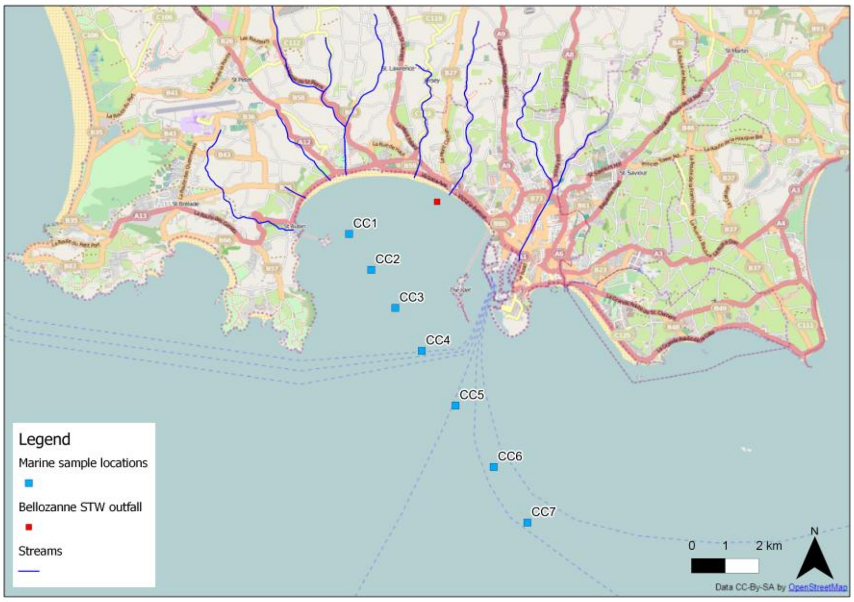


Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

Determinands measured included a range of standard water quality parameters, including DIN (**Figure 3.6-3.9**) and total phosphorus (**Figure 3.10-3.13**). Analysis of the water quality data measured over the winter and spring monitoring periods in St Aubin's Bay show that determinand levels in the bay are commonly several orders of magnitude less than those measured in the streams. These levels are taken to reflect marine baseline conditions since no substantial rainfall derived flow events occurred during sampling.

Figure 3.6 Winter: DIN calculated for the streams

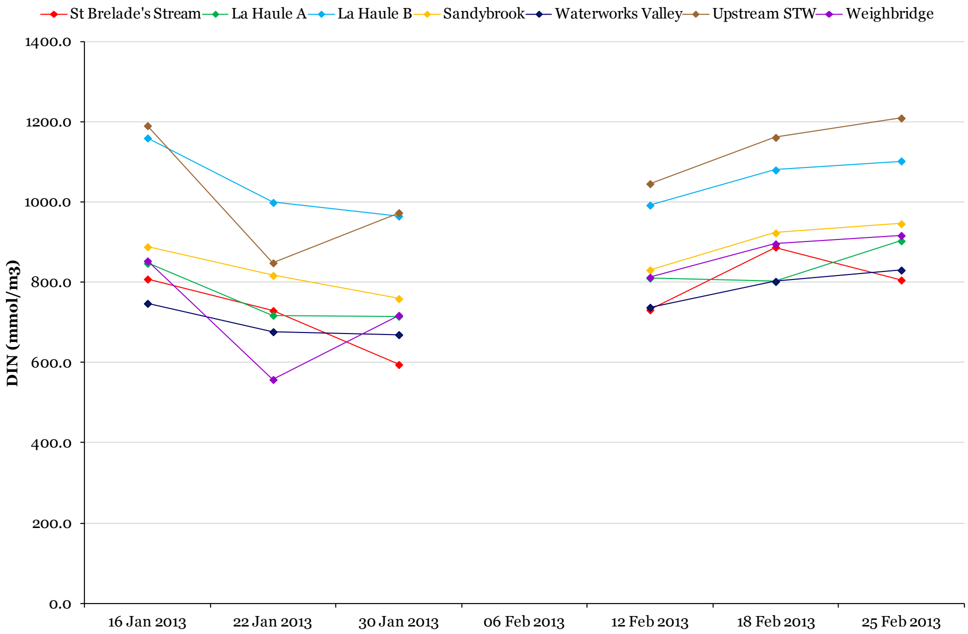


Figure 3.7 Winter: DIN calculated for St Aubin's Bay

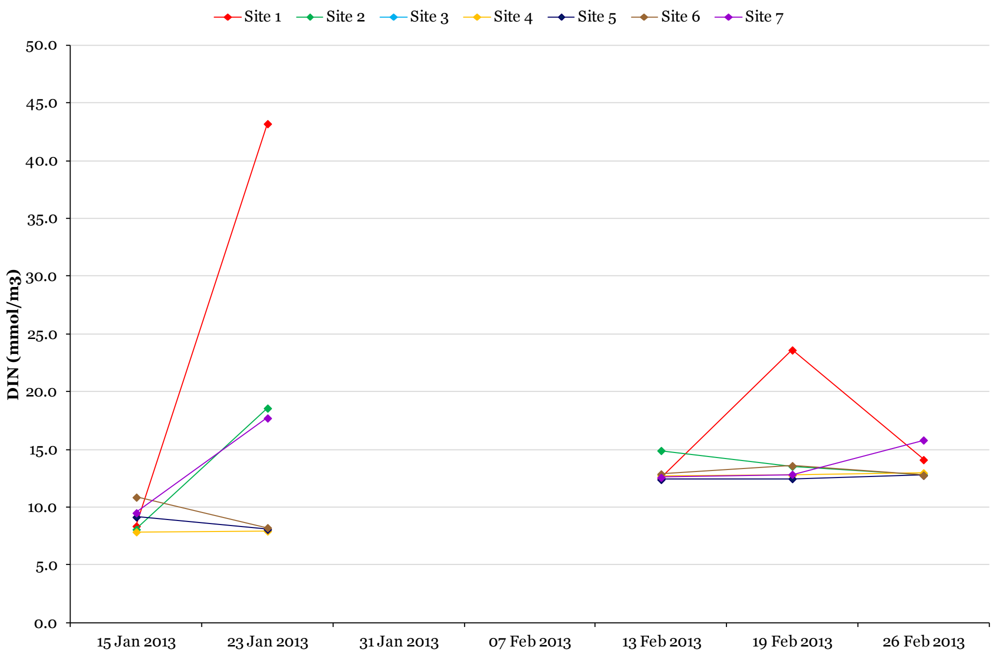


Figure 3.8 Spring: DIN calculated for the streams

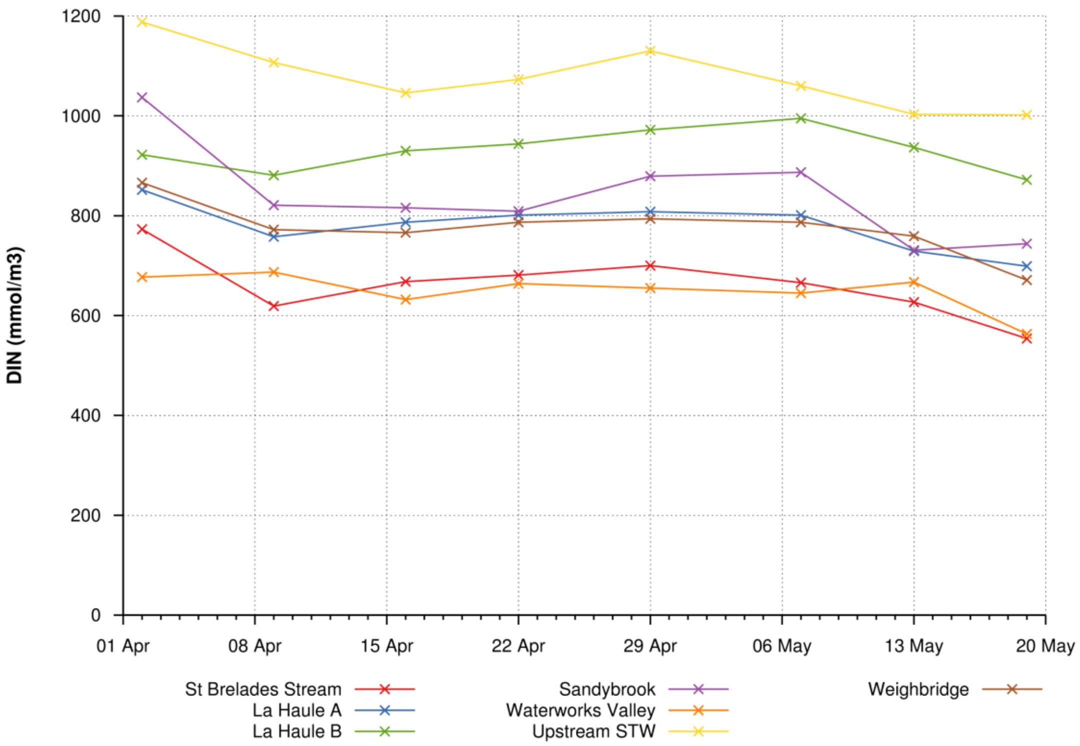


Figure 3.9 Spring: DIN calculated for St Aubin's Bay

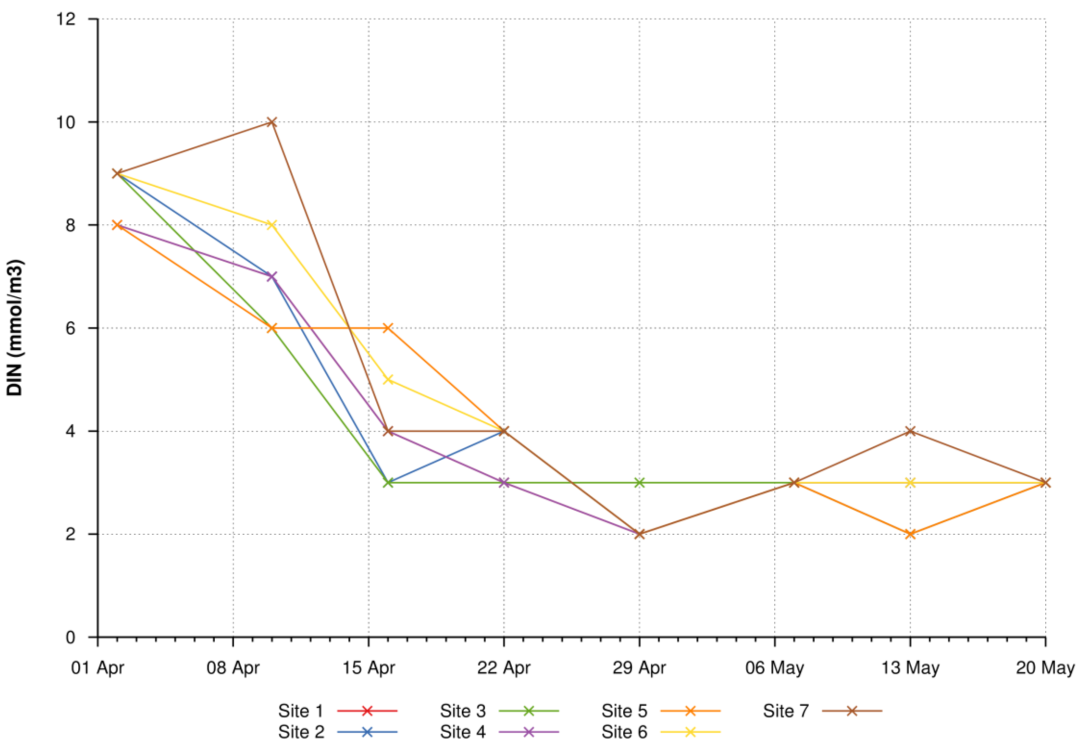


Figure 3.10 Winter: Total phosphorus measured in streams

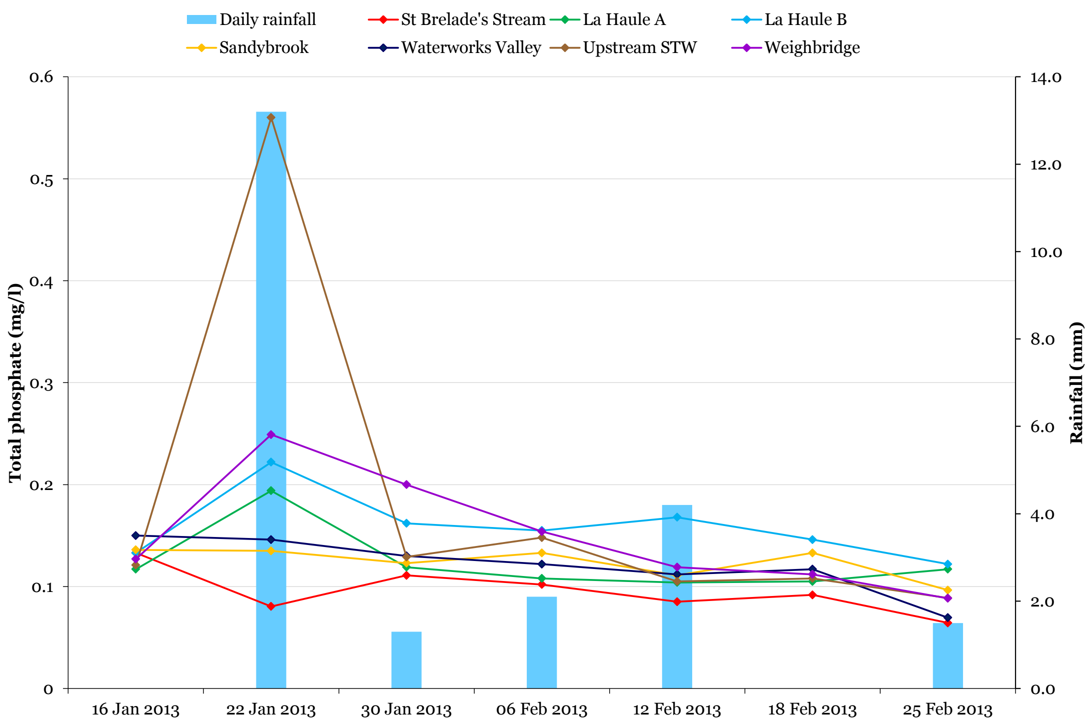


Figure 3.11 Winter: Total phosphorus measured in St Aubin's Bay

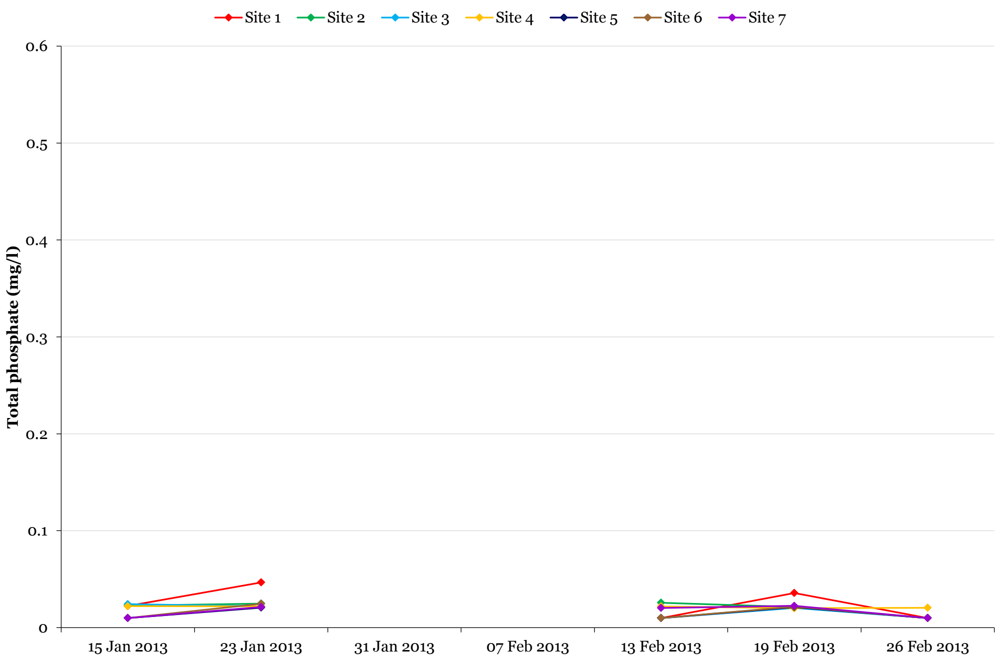


Figure 3.12 Spring: Total phosphorus measured in streams

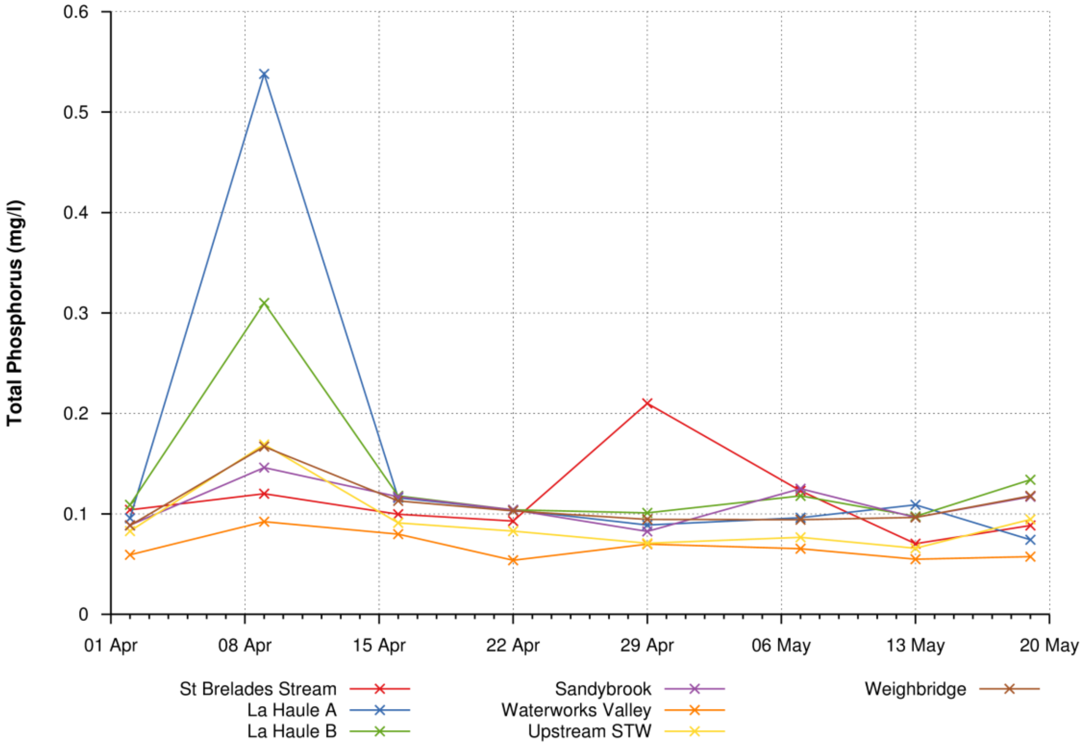
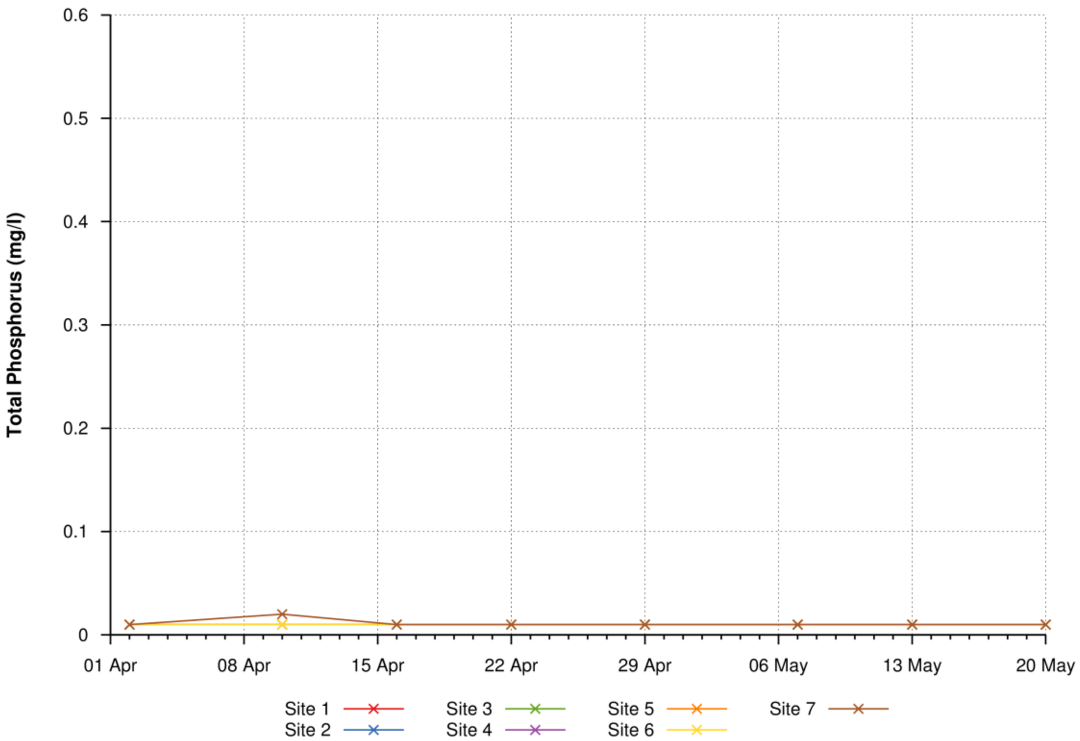


Figure 3.13 Spring: Total phosphorus measured in St Aubin's Bay



For the majority of determinands, no correlation was found between the measured determinand concentrations in the stream and marine environments during both winter and spring monitoring (**Figures 3.6-3.13**). The water quality in the Bay was found to be relatively consistent, with no persistent and identifiable impact from the stream and/or STW inputs.

The results of the winter and spring monitoring and previous studies[97] indicate that it is likely that the nutrient inputs from the wider marine environment (as evidenced by a separate offshore marine transect study; Section 3.1) are exerting impacts on the Bay as least as great as the stream and STW nutrient inputs.

Spring monitoring succeeded in capturing the spring algal bloom within St Aubin's Bay, which is triggered by the presence of significant nutrient levels. Although measured nitrogen concentrations in the bay over the winter were measured as being elevated, these were insufficient to allow a sustained nuisance phytoplankton bloom to form (requiring levels above 10μg/l). The data suggested that for this spring period, there was no evidence of eutrophication.

3.3 COMPARISON WITH BLOOM REQUIREMENTS

Section 2 established that the nitrogen level for bloom conditions is around 10mmol/m^3 DIN, although when in the season this occurs remains to be confirmed (whether at the end of winter of into the spring bloom period). Concentrations in St Aubin's Bay exceed these levels in winter, often significantly, with peaks at Site 1 reaching 20-40mmol/m^3 DIN, although concentrations generally remained around 10-15mmol/m^3 (see **Figure 3.7**). Levels of DIN in the streams feeding into St Aubin's Bay are much higher, in the region of 600-1200 mmol/m^3 (**Figure 3.6**).

Whilst the environment in St Aubin's Bay throughout the winter provides nutrients at levels able to trigger prolific growth of *Ulva*, at that time of the year temperature and light are limiting for production, thus growth of *Ulva* remains low. The 2013 marine transect data confirms that by early spring (mid-March) levels in St Aubin's Bay, and the surrounding waters, were around 8-9mmol/m^3 DIN (**Figure 3.2**), just below the level for prolific growth. However, sampling in 2013 also found water temperatures in March remain below 8C[98], too low for rapid growth in *Ulva*.

Light levels and temperatures become adequate for growth later in the spring, with seawater temperatures in St Aubin's Bay raising above 10C in April-May in most years[99]. However, during this time period nutrient levels in the Bay drop from 8-10mmol/m^3 in early April to <5mmol/m^3 by late April (**Figure 3.9**), a level well

97 CREH (2010) *Reassessment of the trophic status of St Aubin's Bay, Jersey 2009-2010*. A report to Transport and Technical Services, States of Jersey.
98 Cascade Consulting (2013) *Review of available historic freshwater and marine data from St Aubin's Bay and surrounding areas*, Report to States of Jersey, TTS
99 Monthly mean sea temperature at St Helier Harbour data, provided by Martin Gautier, States of Jersey Transport & Technical Services , Assistant Director - Technical Services.

below that required for blooms. Whilst the early spring concentration of 8mmol/m^3 DIN is adequate for healthy growth of *Ulva*, there is no evidence that this level of nitrogen is enough to trigger green tides, particularly when the levels are not maintained. The lack of an *Ulva* bloom in the spring and summer of 2013[100] is consistent with this assumption.

Monitoring data are also available for the spring and summer of 2010[101]. Median levels of DIN at various sites monitored were in the range 1.1-2.4 mmol/m^3. Although maximal levels did reach 18.7 mmol/m^3 at a site in the middle of the Bay, these generally low levels are not high enough to support consistently high growth. Similarly to 2013, no green tide formed in St Aubin's Bay in 2010.

The levels of nutrients in streams discharging into St Aubin's Bay are an order of magnitude higher than those within the Bay. For nutrient levels to remain high throughout the spring and summer a continual influx of nutrients from land based sources or the wider marine environment would be required. The shallow, sheltered nature of St Aubin's Bay provides a relatively enclosed tidal system, potentially increasing the residence time of nutrients. The levels in the Bay, at least in spring, are largely controlled by the wider marine environment, as evidenced by the marine transect data (**Figure 3.2**). These levels, at 8-9 mmol/m^3 DIN, remain close to the threshold for bloom occurrence and thus the input of nutrients from land based sources may not need to be very large to increase nitrogen levels beyond the trigger for green tide formation. Rainfall may be a key factor in the transfer of pulse loads of enough nutrients to the Bay[102]. The two worst blooms in recent years, 2007 and 2012, were both in years with high summer rainfall[103].

The influence of temperature on growth rate means that if seawaters warm up earlier in the spring than usual, this may coincide with high nutrient levels, allowing a proliferation of *Ulva*. The seawater temperature in St Aubin's Bay was warmer than usual in the winters 2006/07 and 2011/12, with the temperatures in January 2007 and 2012 were recorded as 10.2C and 10.0C respectively[104]. A large green tide formed in St Aubin's Bay in both the summer of 2007 and of 2012, providing some support for the idea that warmer water temperatures in the winter and early spring enabled *Ulva* to make use of the high nutrient levels in the Bay at the point at which light levels became adequate for growth.

Water quality monitoring data for St Aubin's Bay were collected in 2012[105], but

100 *Pers.comm.* Martin Gautier, States of Jersey Transport & Technical Services , Assistant Director - Technical Services, via email 15 August 2013.
101 CREH (2010) *Reassessment of the trophic status of St Aubin's Bay, Jersey 2009-2010*. A report to Transport and Technical Services, States of Jersey
102 *Pers comm*, Steve Landick, States of Jersey Transport & Technical Services Assistant Manager Cleaning Services, via email to Martin Gautier 21 August 2013.
103 Monthly rainfall at Maison St Louis Observatory data, provided by Martin Gautier, States of Jersey Transport & Technical Services, Assistant Director - Technical Services.
104 Monthly mean sea temperature at St Helier Harbour data, provided by Martin Gautier, States of Jersey Transport & Technical Services, Assistant Director - Technical Services.
105 WCA (2012) *WFD monitoring survey for States of Jersey*, Data collection for Department of the Environment.

unfortunately the limit of detection associated with the sample processing was high at 15 mmol/m^3 for DIN. This means it is not possible to establish whether nutrient levels were above bloom thresholds or not.

Salinity and pH was measured during the marine transect survey and were remained at 34-35ppm and pH7-8 throughout the survey. These are typical of coastal waters and do not fall in the range of values likely to cause abnormal growth of *Ulva*.

4 MANAGEMENT RESPONSE TO *ULVA* BLOOMS

The response to *Ulva* blooms in Jersey is to clear algal biomass from the beaches[106]. Clearance of the sea lettuce blooms from the beaches is a significant cost to the States of Jersey. At present, £30,000 per year is spent to remove sea lettuce blooms from selected beaches during the summer months. In the 1990s this algae was disposed of in landfill, however odour and space problems led to the current-day management strategy of disposal to the sea at low tide. This strategy is problematic and not cost effective. Plans to trial the composting of harvested *Ulva* have been made by the States of Jersey, Transport & Technical Service, but the lack of a bloom in 2013 has meant these trials have not occurred to date.

The following section summaries the responses to recent green tides in other parts of the world. In common with Jersey, the most common response to macroalgal blooms is to clear the biomass from beaches, but this biomass is generally disposed of on the land. Longer term responses involve the implementation strategies to reduce the influx of nutrients into coastal waters and thereby reducing the occurrence of green tides.

4.1 KENT

The Thanet coastline is characteristic by sandy beaches and chalk coastline, supporting a diverse macroalgal community[107] (**Figure 4.1**). Macroalgal blooms have been a problem in Thanet since the 1960s, thought initially to be related to an increase in untreated sewage effluent to the marine environment[108]. A particularly large bloom is reported to have occurred in Foreness Bay in 2003 when 9,000 tonnes were collected from the beach, but blooms have also been reported in Bedlams Bottom[109]. The generally high nutrient levels in the English Channel, combined with occasional eutrophication events, has led to this issue remaining despite improvements in coastal discharges. The local authority clears drift algae from beaches, at a cost reported to be £107,000 for a three year clearance contract. The volume of algae cleared is around 150 tonnes per day and can reach 6,000-7,000 tonnes per year[110]. Much of this algae is washed from nearby chalk reefs and consists of perennial species dislodged and washed ashore, but *Ulva* species can form a significant proportion of the biomass.

106States of Jersey (2013*) Beach Seaweed Removal*, TTS Operational Services Directorate Cleaning Services, Technical Briefing Note, 11/07/13
107 Thanet District Council (2013) *Thanet Coat Project*, www.thanetcoast.org.uk, Accessed 21/08/13.
108 Rogers, P.J., Dake, N., Dussart G.B.J. (2004) *Ulva* problem in Kent: 1973–2003 *Marine Pollution Bulletin* 49: 145–146.
109 Rogers, P., Dussart, G. (undated) *Nutrient dynamics and the Thanet coast, power point presentation*, http://www.lsbu.ac.uk/esbe/news/eventsdetail/downloads/thames/ROGERS_nutrients.pdf, Accessed 21/08/13.
110 Thanet District Council (2013) *Seaweed Facts*, http://www.thanet.gov.uk/news/focus_on_news/seaweed_in_thanet/seaweed_facts.aspx, Accessed 21/08/13.

Figure 4.1 Map of Foreness Bay, Thanet, Kent

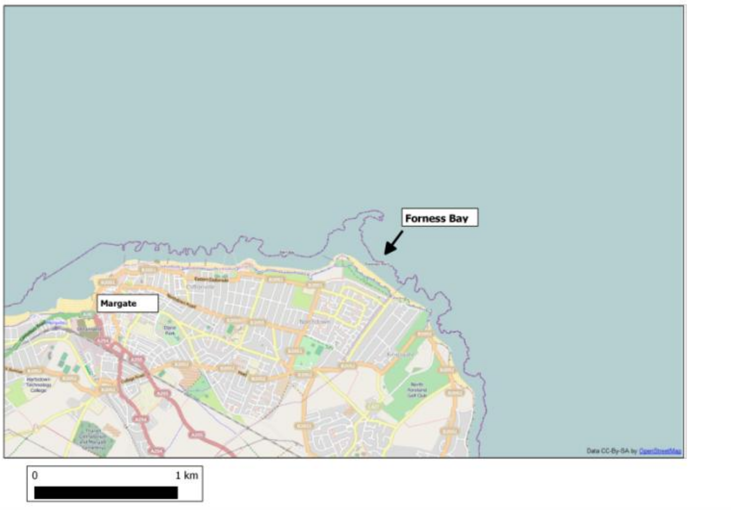


Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

The volume washing ashore bathing beaches is considered a nuisance and is cleared from May-September and transported to farmland. This clearance occurs with permission from Natural England and under guidance from the Environment Agency. This ensures delicate areas such as the chalk reefs are not damaged by clearance activities. During this period the council:

- monitors the coastline daily
- attempts to clear the beaches everyday
- starts clearing the seaweed from 4am to ensure the beaches are clear for beach users
- target the priority areas first - popular bays where there are beach huts and bathers, or areas with very high levels of seaweed
- target areas based on daily reports from contacts around the coast
- has a dedicated officer who coordinates the removal of seaweed and a dedicated budget to cover this
- hires special machinery throughout the summer to remove the seaweed - a telehandler JCB
- on days with a higher amount of seaweed brings in extra staff and machinery from contractors to deal with the problem

4.2 CORK, IRELAND

Problems with *Ulva* accumulation on beaches have been increasing in recent years and in 2009 the volume of algae collected from the regions beaches was 10,000 tonnes[111]. The accumulation of *Ulva* in Clonakilty and Courtmacsherry Bay (**Figures 4.2** and **4.3**) are responsible for current failures under the Water Framework Directive (WFD) due to the 'poor' status of the macroalgal community. The key management actions are being undertaken to deal with the causes of the blooms. These actions include improvement of wastewater treatment and inspection of farms in relevant river catchments in order to reduce the influx of nutrients into the coastal waters. Both Clonakilty and Courtmacsherry Bay are tidal bays providing a large area of sheltered waters.

Figure 4.2 Map of Clonakilty Bay, Cork, Ireland

Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

Figure 4.2 Map of Courtmacsherry Bay, Cork, Ireland

Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

The local council, Cork County Council, has dealt with the *Ulva* spp. accumulation in the past by collecting, stockpiling and/or discharging collected biomass to the sea. However, complaints from the fishing industry in 2009 triggered an investigation

[111]Department of Environment Ireland (2010) *Sea lettuce task force report*

which concluded that dumping at sea was not compliant with the Dumping at Sea Act 1996. Stockpiling on remote beaches was also discounted as an option at that time due to increasing concerns over health issues relating to hydrogen sulphide accumulations. Cork County Council then reverted back to the discharging of *Ulva* biomass. back to the sea on the ebb tide.

Given the volume of *Ulva* collected and the ongoing nature of the problem, the Cork County Council has investigated methods for compressing the volume of biomass collected and for utilisation of the material. The options identified were:

- utilisation as fertiliser for spreading on farmland located in the vicinity of the affected beaches
- utilisation as a soil enhancer for capping landfill cells
- transportation to commercial composting facilities for local composting sites
- transportation and disposal to landfill under appropriate agency approval.

The logistics, costs and benefits of these options were explored further. It was estimated that 1500-3,000 tonnes of *Ulva* could be utilised as fertiliser at 15 nearby farms at an estimated cost of €24,000-48,000. Waste handling sites could utilise 5,000-8,000 tonnes for composting at a cost of €335,000-536,000.

4.3 BRITTANY

Brittany has a long coastline with numerous large sandy beaches as well as large granite cliffs and reefs. Brittany has experienced serious problems with green tides over the past few decades, causing serious issues for the tourism industry[112] at beaches such as Hillion and Morieux near Saint-Brieuc (**Figure 4.3**). The enhanced growth of *Ulva* is thought to result primarily from agriculturally based leaching of fertilised soil by rainwater[113], although the French government has downplayed the role of agriculture[114]. The region supports a large livestock farming industry resulting in significant inputs of nutrients to the land. An influx of substantial nitrogen supplies from rivers during June is thought to be a key factor in triggering green tides[115].

112 Viscusi, G. (2011) *'Green Tides' Drive Away Brittany Tourists*, 3/8/08, http://www.bloomberg.com/news/2011-08-03/brittany-green-tides-drive-away-tourists-from-french-beaches.html, Accessed 21/08/13
113 Charlier, R.H., Morand, P., Finkl, C.W. (2008) How Brittany and Florida coasts cope with green tides, International *Journal of Environmental Studies*, 65:2, 191-208
114 Coastal Care (2011) *Wild Boar Deaths linked to Green Algae: Confirmed*, 6/8/08, http://coastalcare.org/2011/08/wild-boar-deaths-linked-to-green-algae-confirmed/, Accessed 21/08/13
115 Ménesguen, A., Piriou, J-Y., (1995) Nitrogen loadings and macroalgal (*Ulva* sp.) Mass Accumulation in Brittany (France), *Ophelia* 42:227-2

Figure 4.4 Map of Hillion & Morieux Bays, Brittany, France

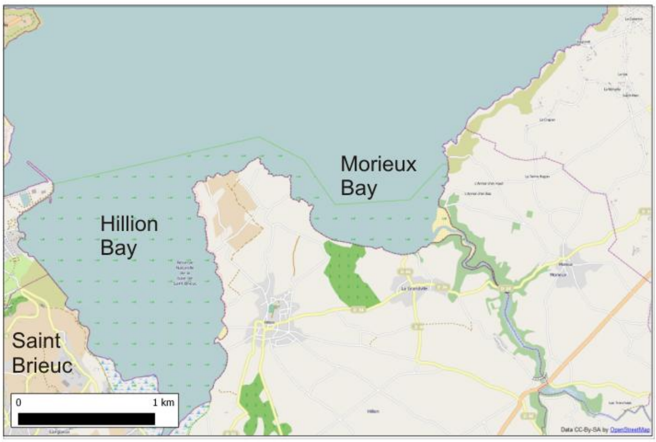


Figure base map © OpenStreetMap contributors (http://www.openstreetmap.org/copyright).

Reports of green tides in Brittany date from the 1960s[116],[117] and nowadays almost all coastal municipalities engage in some level of collection of green tide algae[118]. The green tides consist mainly of *Ulva* species. and are harvested in large quantities, up to 100,000m^3 per annum. Expenses in 2004 reached €610,000 for the combined Brittany region[119].

Reports have been made of animal (horse and pig) deaths following exposure to the large amount of hydrogen sulphide accumulating during the decomposition process[120,121,122]. The numbers of tourists decline during green tides, caused by the presence of *Ulva* in the water deterring bathing and by the odour on beaches from decomposing biomass[123]. The accumulation is considered large enough to require harvesting from beaches in order to minimise economic consequences on the tourism industry.

Methods for cleaning the beaches include sifting machines, raking machines and scraping machines. The loss of sand from beaches can be significant during this process; for example 500 tonnes of sand per year are lost from Lannion Bay in

116 Merceron, M., Antoine, V., Auby, I., Morand, P. (2007) In situ growth potential of the subtidal part of green tide forming *Ulva* spp. stocks, *Science of The Total Environment* 384: 293-305.
117 Bretagne Environnement (2013) Brittany clean water and Prolittoral http://www.bretagne-environnement.org/Eau/Quelles-actions/Grand-projet-5/Bretagne-eau-pure-et-Prolittoral-les-precurseurs-du-GP5, Accessed 02/10/13
118 Charlier, R.H., Morand, P., Finkl, C.W., Thys, A. (2007) Green Tides on the Brittany Coasts, *Environmental Research, Engineering and Management* 3:52-59.
119 Charlier, R.H., Morand, P., Finkl, C.W. (2008) How Brittany and Florida coasts cope with green tides, *International Journal of Environmental Studies*, 65:2, 191-208.
120 Robic, A., Sassi, J.F., Dion, P., Lerat, Y. (2009) Seasonal variability of physiochemical and rheological properties of ulvan in two *Ulva* species (Chlorophyta) from the Brittany coast, *Journal of Phycology* 45, 962–973.
121 BBC (2009) *Toxic seaweed clogs French coast*, 11/08/2009, http://news.bbc.co.uk/1/hi/8195180.stm, Accessed 21/08/13
122 BBC (2011) *France: Wild boars dead amid algae on Brittany coast*, 28/07/2011, http://www.bbc.co.uk/news/world-europe-14324094, Accessed 21/08/13.
123 Bolis, A. (2011) *One Year On Green Algae Are More Than Ever Plaguing Brittany's Beaches*, 08/08/2011, Translated report from LeMonde, http://coastalcare.org/2011/08/toxic-algae-still-turns-brittanys-beaches-green/, Accessed 21/08/13.

Brittany[124].

The harvested algae is used where possible as fertiliser or mixed with waste to be composted. Some of the biomass is also dehydrated and mixed with poultry feed. In some cases however, dumping of large volumes of *Ulva* biomass has created land based pollution problems. This has led to research into the use and commercialisation of the harvested algae[125,126,127].

The French government has invested considerable resources into investigating green tides over the past two decades. The 2002-2006 'Prolittoral' program was coordinated by the Centre for Study and Development of Algae/Centre d'Etude et de Valorisation des Algues (CEVA) and funded by a range of regional partners in Brittany, including the Region of Brittany, the Water Agency of Loire and Brittany and the four local départements in Brittany. It focused on preventative measures, such as reduction in nitrate runoff, investigations into effective management measures, as well as the monitoring of green tide events. The 'Brittany Clean Water/Le Programme Bretagne Eau Pure' ran concurrently with Prolittoral and focused on the restoring of water quality in Brittany.

In 2007 these programs were replaced by Grand Project 5 (GP5) which has the primary aim of achieving good status in aquatic environments under the Water Framework Directive.

In addition, in 2010 the French Government released a technical report 'Elaboration d'un plan de lutte contre les algues vertes' and an associated action plan 'A plan against green algae/'Plan National de Lutte Contre les Algues Vertes[128]' to tackle green tides. This plan contains three components:

- Ensuring proper management of green tides- including collection and composting
- Enforcing existing regulations– including farmer engagement on nitrate runoff, using Saint Brieuc and Lannion as pilot study bays then expanding to an additional six bays
- Measures to achieve a reduction in nitrate runoff of 30-40% by 2015- including the creation of biogas plants.

124 Charlier, R.H., Morand, P., Finkl, C.W., Thys, A. (2007) Green Tides on the Brittany Coasts, Environmental Research, Engineering and Management 3:52-59
125 Charlier, R.H., Morand, P., Finkl, C.W., Thys, A. (2007) Green Tides on the Brittany Coasts, *Environmental Research, Engineering and Management* 3:52-59
126 Bruhn, A., Dahl, J., Nielsen, H.B., Nikolaisen, L., Rasmussen, M.B., Markager, S., Olesen, B., Jensen, P.D. (2011) Bioenergy potential of *Ulva lactuca*: Biomass yield, methane production and combustion, *Bioresource Technology* 102: 2595–2604
127 Briand, X., Morand, P. (1997) Anaerobic digestion of *Ulva* sp. 1. Relationship between *Ulva* composition and methanisation, *Journal of Applied Phycology* 9: 511–524.
128 Republique Francaise (2010) *Plan de lutte contre les algues vertes*, http://www.developpement-durable.gouv.fr/IMG/pdf/Plan_de_lutte_contre_les_algues_vertes.pdf, Accessed 02/10/13

Under the action plan, existing plants for drying and composting algae will be supported by new facilities, costing an estimated €16 million. The plan also contains options for using *Ulva* biomass as agricultural fertiliser in areas distant from processing facilities. Plans to reduce the application of mineral fertiliser are based on the use of biogas plants to create anerobic digestate from manure, and then utilise this as a fertilser.

The GP 5 is due for completion in 2013. It is recommended that the outputs of any projects and pilot studies within GP5 which relate to green tides be reviewed for relevance to the situation in Jersey.

4.4 PORTUGAL

Macroalgal blooms have been a frequent occurrence in the Mondego estuary, Portugal over the last 20 years[129]. Seagrass beds in the estuary have been impacted by the blooms and adverse impacts were also felt by the local aquaculture industry. In the late 1990s a set of experimental mitigation measures were installed to control the eutrophication process. These measures reduced the nutrient loading and residence time in the estuary. Blooms have not been recorded in the post-mitigation period, indicating successful reduction in nutrient levels[130]. However, there is evidence that the history of eutrophication has lowered the resilience of the system to stressful natural-induced events such strong floods. Recovery of the seagrass system to such events was slower, with a lowered benthic productivity rate and species richness than that observed in pristine systems.

4.5 ITALY

The Sacca di Goro (Goro Lagoon) is characterised by anthropogenic eutrophication and experiences recurrent *Ulva* blooms[131]. The viability of aquaculture activities within the lagoon is threatened by the low oxygen content of the waters resulting from these blooms so lagoon managers are forced to reduce the algal biomass through harvesting.

The present strategy to control algal blooms relies on harvesting vessels rented from a third part company at an annual cost of €40,000-60,000. The lagoon managers sign a contract at the beginning of the year to rent two vessels that are then used jointly along the *Ulva* growing season for no more than 10–15 days, meaning managers must be very conservative when using the vessels. The vessels only operate in the area where clam fisheries are located and tend not to be deployed until *Ulva* blooms are well advanced.

129 Dolbeth, M., Cardoso, P., Pardal, M.A. (2011) Impact of Eutrophication on the Seagrass Assemblages of the Mondego Estuary (Portugal), In: A.A. Ansari et al. (eds.), *Eutrophication: Causes, Consequences and Control*, Springer Science

130 Dolbeth, M., Cardoso, P.G., Ferreir,a S.M., Verdelhos, T., Raffaelli, D., Pardal, M.A. (2007) Anthropogenic and natural disturbance effects on a macrobenthic estuarine community over a 10-year period, *Marine Pollution Bulletin* 54:576–585.

131Cellina, F., De Leo, G.A., Rizzoli, A.E., Viaroli, P., Bartoli, M. (2003) Economic modelling as a tool to support macroalgal bloom management: a case study (Sacca di Goro, Po river delta) *Oceanologica Acta* 26:139–147.

Modelling of the effectiveness of this strategy and alternative strategies revealed that management practises based on a lower threshold density are generally more effective, suggesting that harvesting at the beginning of the bloom is the most effective way to control the bloom and avoid anoxic crises. If the threshold density (the density at which managers decide to act) is greater than 100 gDWm-2 there is little chance of controlling algal blooms, regardless of the number of vessels deployed. The current practise of using two vessels when the bloom is well advanced on only 10-15 days per year is therefore ineffective. In addition, harvesting is currently restricted to the period March-July and the modelling revealed this delay in intervention was wasted effort as it did not target the population early enough in the bloom cycle.

4.6 CHINA

The large green tide in the Yellow Sea in June 2008 was located on the shores of Qingdao, the Olympic sailing venue, and a massive clearance operation was required to ensure the sailing event was not interrupted. The clean-up required 10,000 people and removed over one million tonnes from the beach and nearshore coastal waters[132]. Clean-up operations have been required in all in subsequent years, with 2000 people deployed to clear the early summer bloom in 2013.[133]

Green tides have continued to form in subsequent years and even if commercial exploitation of the harvested biomass is established[134] it has been concluded by that that it will not offset the continued bill for cleaning up the algal biomass or compensate for the serious ecological consequences which result[135]. Initial responses by tourists to the green tide may include positive reactions to the novelty of swimming in *Ulva*, but the city of Qingdao relies on its beaches for its tourism industry and it is generally viewed as a problem[136].

132 Keesing, J.K., Liu, D., Fearns, P., Garcia, R., 2011. Inter- and intra-annual patterns of *Ulva prolifera* green tides in the Yellow Sea during 2007e2009, their origin and relationship to the expansion of coastal seaweed aquaculture in China. *Marine Pollution Bulletin* 62, 1169-1182
133 South China Morning Post (2013) *Seaweed farming linked to Qingdao's green tide of algae*, 17/07/2013, http://www.scmp.com/news/china/article/1284156/cause-qingdaos-green-tide-algae-mystery, Accessed 214/08/13
134 Liu, D., Keesing, J.K., He,P., Wang, Z., Shi, Y. (2013) The world's largest macroalgal bloom in the Yellow Sea, China: Formation and implications, *Estuarine, Coastal and Shelf Science* 129: 2-10.
135 Keesing, J.K., Liu, D., Fearns, P., Garcia, R., 2011. Inter- and intra-annual patterns of *Ulva prolifera* green tides in the Yellow Sea during 2007e2009, their origin and relationship to the expansion of coastal seaweed aquaculture in China. *Marine Pollution Bulletin* 62, 1169-1182
136 AFP (2013) *China's 'green tide' thanks to largest ever algae growth*, 04/07/2013, http://www.rawstory.com/rs/2013/07/04/chinas-green-tide-thanks-to-largest-ever-algae-growth/, Accessed 21/08/13

5 CONCLUSIONS

Ulva species are found along all but the most wave exposed coastlines around the world. They are opportunistic species, capable of very rapid expansion in population size. This leads to the formation of green tides, which can lead to serious ecological and economic consequences. This report documents the available literature identifying the factors controlling the growth of *Ulva*, and relates them to the conditions currently found in St Aubin's Bay.

The review has established that light conditions must be adequate for growth and that temperatures of 15-20 °C provide optimal conditions for growth, but that active growth begins at around 10 °C. The timing of this threshold in spring is critical to future potential for bloom formation. Once light and temperature conditions are favourable the growth of *Ulva* is largely controlled by nutrient levels, in particular nitrogen concentrations. High levels of nitrogen in coastal waters in the early summer thus will provide ideal conditions for *Ulva* growth, but high concentrations earlier in the year will have a much lower effect on growth rate as seawater temperatures at this time are too low for significant growth.

The nitrogen level required for bloom conditions would appear from the literature to be around 10mmol/m^3 DIN, although the critical seasonal timing (spring through to late summer) at which the levels occur remains unclear. In 2013 the nutrient conditions in the Bay fell below this threshold (probably from wider phytoplankton uptake) by the time light and temperature levels were adequate for active growth of *Ulva* in spring. No *Ulva* bloom has so far been recorded over the summer of 2013. By contrast, in 2012 and 2007, both years in which large *Ulva* blooms occurred, the seawater temperatures in St Aubin's Bay were recorded as 10.2C and 10.0C, respectively in January. This indicates that further investigations into the role of temperature as well as nutrient conditions in the Bay are needed to enable a better understanding of the combination of conditions which result in a bloom.

One key conclusion however, is that the STW discharge <u>in isolation</u> does not create the algal blooms. Green tides are intermittent and do not occur every year, although the nutrient levels within the discharge are relatively consistent year on year. Should the STW be solely responsible on its own there would be blooms every year. Green tides are therefore triggered by a more complex set of environmental and anthropogenic factors which includes the contribution from the STW. Other environmental conditions/inputs include general climatic conditions and combined nutrient loads from the wider marine sources and a changeable combination of land based derived nutrient loads. The impact of a changing climate is likely to be an increasing pressure on bloom formation.

The current response to green tides in Jersey is to harvest algae from selected beaches and dispose of at low tide. The most common current response to macroalgal blooms in other countries is to clear the biomass from beaches and dump elsewhere, with the most efficient strategy suggested to be harvesting early in the bloom cycle. However, many municipalities are now exploring ways in which to utilise the collected biomass and to avoid dumping on land.

Longer term responses involve implementing strategies to reduce the influx of nutrients into coastal waters and thereby reducing the occurrence of green tides. Given the probable significance of the wider marine environment on St Aubin's Bay nutrient status, implementation of such strategies in Jersey would require simultaneous implementation in nearby countries in order to be successful.

6 RECOMMENDATIONS

1. More data are required to establish the complex interaction of nutrient, temperature and hydrological conditions necessary for an *Ulva* bloom in St Aubin's Bay. Monitoring of the relative load contributions from the wider marine environment, the STW and from other land based runoff towards nutrient conditions in the Bay, along with more frequent Bay temperature and hydrodynamic data, will enable managers to better predict the timing of a bloom.

2. A measure for *Ulva* biomass is required to compare productivity with prevailing environmental conditions. This will allow the relationship between *Ulva* growth to be analysed against environmental conditions, leading to a defined bloom trigger analysis and action plan. This is the first key step needed before management strategies to cope with *Ulva* blooms can be more efficiently implemented.

3. A longer term nutrient control strategy is required. It must consider all significant loads over the full seasonal and inter-annual cycle to promote an integrated catchment and marine management strategy.

4. The existence of additional management measures, including the utilisation of harvested biomass, has been noted throughout the production of this report, however it has not been the focus of the review. It would be useful for the States of Jersey to further investigate the experience of others and the available literature for management measures to determine which would be most suitable for trialling in St Aubin's Bay.

5. Additional work on selected sites suffering from green tides, such as those in southern Ireland and the eastern English Channel in France, could enable a comparison of these sites with St Aubin's Bay to establish the similarities and differences in hydrodynamics and water quality as well as ecology. A nutrient budget of the Bay, with *Ulva* growth as key parameter, could be created to enable better management of the nutrient flow into the Bay in order to minimise the likely development of green tides.

6. The changing climate will have an increasing effect on the Bay and near coast ecosystems, and may lead to increasing nuisance bloom formation as sea temperatures rise in winter and spring. A study of the implications of climate change on the marine ecosystem is recommended.

7. Further time could usefully be spent on French literature to see if data and evidence are available. It is likely that such data do exist as the problems in French bays are well established.