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The Effects of Turbidity on Suspension Feeding Bivalves

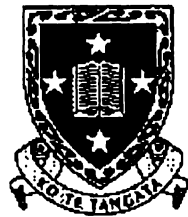
A thesis submitted in partial fulfillment of the requirements
for the degree of

Master of Science

in Biological Science
at
the University of Waikato

by

Iannang Teaioro



March 1999
Hamilton, New Zealand

For my Father

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Abstract

This thesis aimed to describe the relationship between suspended sediment concentration stimulating the turbidity caused by natural events or human activities, and the feeding behaviour and energetics of scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*) and pipis (*Paphies australis*). A wide range of suspended sediment concentration with different organic content was used. In experiment 1, sediment with high organic content added to natural seston (12 – 733 mg l⁻¹) was used, whereas in experiment 2, sediment with very low organic content added to natural seston (20 – 196 mg l⁻¹) was used. Scallops enhanced the organic content of ingested matter by producing pseudofaeces with low organic content when the diet organic content had been diluted to $\leq 14\%$ in both experiments. For the diet with high organic content, the clearance rate (the volume of water cleared of suspended particles) decreased with increasing sediment concentration (12 – 733 mg l⁻¹), but when the diet was composed of low organic content, clearance rate increased up to a concentration limit of 120-140 mg l⁻¹. Positive scope for growth was attained until suspended sediment concentration exceeded 190 mg l⁻¹. Similarly, mussels also enhanced the organic content of ingested matter by producing pseudofaeces with low organic content when the diet organic content had been diluted to $\leq 16\%$ in both experiments. The enhancement of ingested organic fraction was accomplished by two different feeding behaviours. When the diet had high organic content, mussels clear less water, reduce the volume of pseudofaeces produced, and reduce the amount of energy expired via low respiration rates. Consequently, the net energy gained was uniformly high as sediment concentrations increased to 322 mg l⁻¹. The low organic diet prompted high clearance rates and increase in pseudofaeces production as

sediment concentration increased. Due to high feeding activities, energy expenditure was also high which was reflected in a low net energy gain. Papis can only feed efficiently at very low sediment concentrations ($<39 \text{ mg l}^{-1}$ in experiment 1 and 20.1 mg l^{-1} in experiment 2). Beyond these values, papis were unable to compensate for increased sediment concentration and therefore had very low scope for growth.

From these results it was concluded that preferential selection of organic particles before ingestion, adjusting clearance and respiration rates, within limits, are the key elements that enable scallops and mussels to cope with high turbidity levels. Papis have a low tolerance level to turbidity.

The second aim of the study was to investigate the effects of resuspended sediments caused by dredging on seston quality (organic content and pigment concentration) and quantity. This was accomplished through water sampling at various places while dredging was in operation. The results indicated that suspended sediments caused by dredging had no significant effect on the seston quality and quantity, in relation to the seston characteristics observed naturally.

List of Symbols and Abbreviations

Symbol	Definition	Units
<i>AB</i>	absorbed ration (energy gain)	$\text{J h}^{-1} \text{g}^{-1}$
<i>AE</i>	absorption efficiency	fraction
<i>CI</i>	compensation index	-
<i>CR</i>	clearance rate	$\text{l h}^{-1} \text{g}^{-1}$
<i>Diet</i> _{total pigment}	total pigment in diet	$\mu\text{g mg}^{-1}$
<i>DOF</i>	diet organic fraction	fraction
<i>ER</i>	egestion rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>FR</i>	filtration rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>IER</i>	inorganic egestion rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>IFR</i>	inorganic filtration rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>IOF</i>	ingested organic fraction	fraction
<i>IR</i>	ingestion rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>IR</i> _{total pigment}	total pigment ingested	$\mu\text{g mg}^{-1}$
<i>IRR</i>	inorganic rejection rate	$\text{mg h}^{-1} \text{g}^{-1}$
$[\text{O}_2]_{\text{final}}$	final oxygen concentration	ml O_2
$[\text{O}_2]_{\text{initial}}$	initial oxygen concentration	ml O_2
<i>OAR</i>	organic absorption rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>OER</i>	organic egestion rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>OFR</i>	organic filtration rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>OIR</i>	organic ingestion rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>ORR</i>	organic rejection rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>PIM</i>	particulate inorganic matter	mg l^{-1}
<i>POM</i>	particulate organic matter	mg l^{-1}
<i>PSF</i> _{total pigment}	total pigment in pseudofaeces	$\mu\text{g mg}^{-1}$
<i>R</i>	respiration (energy loss)	$\text{J h}^{-1} \text{g}^{-1}$

<i>RR</i>	rejection rate	$\text{mg h}^{-1} \text{g}^{-1}$
<i>SFG</i>	scope for growth	$\text{J h}^{-1} \text{g}^{-1}$
<i>ti</i>	time between successive O_2 measurements	hr
<i>TPM</i>	total particulate matter	mg l^{-1}
<i>U</i>	ammonia excretion (energy loss)	$\text{J h}^{-1} \text{g}^{-1}$
<i>Vi</i>	volume of respiration chamber	l
<i>VO₂</i>	oxygen consumption rate	$\text{ml O}_2 \text{ h}^{-1}$
<i>Y_e</i>	uncorrected physiological measurement	depends on paramet
<i>Y_s</i>	standardised physiological measurement	depends on paramet
<i>W_e</i>	uncorrected weight of animal	g
<i>W_s</i>	standardised weight of animal	g

Acknowledgements

The completion of this thesis was made possible by the assistance and supports of many people. Firstly, I would like to thank my supervisors Professor Terry Healy and Dr. Conrad Pilditch for initiating this project with the Port of Tauranga.

I owe a great deal to Dr. Conrad Pilditch whose meticulous attention and care for minute details on the analysis and structure gave me confidence to complete. His patience to my unthoughtfulness at times is highly appreciated. The comments and criticisms by Professor Terry Healy on the last draft have been invaluable. Also, the editorial help and suggestions provided by Helen Kettles is greatly appreciated.

The assistance provided by Dudley Bell and Ross Butlers in the field, especially in the collection of the bivalves and sediments used in this study, Paul Busing for showing me how to use the respiration chambers, I am grateful and very much indebted.

I am also grateful to Owen Mayard from the Port of Tauranga for arranging the dredging operation in the passage, and the crew of the Port of Tauranga Survey Boat who has made it possible to get those much needed water samples. The help provided by Rutiana Tekitanga in the collection of these samples is very much appreciated.

Lastly, many thanks to my wonderful family, my wife who has become my teacher during the course of writing and my kids who in their special ways have encouraged me throughout these two and half years. I am also thankful to mum who has been helping to look after the kids while trying to study and to the Raoren family, thank you for making me realise that Hamilton is a very good place to stay.

To everyone who has helped in many different ways, thank you.

Te Mauri, Te Raoi, ao Te Tabemoa

CHAPTER 1

Introduction

Turbidity is an expression of the optical property of the water that causes light to be scattered and absorbed rather than transmitted in straight lines (American Public Health Association, 1992). In water, turbidity is caused by suspended matter which include clay, silt, fine divided organic and inorganic matter, soluble coloured organic compounds, and plankton and other microscopic organisms. This suspended particulate matter (*SPM*) is commonly referred to as “seston” (Fegley *et al.*, 1992).

Suspended natural seston fluctuates substantially from very low to hundreds of mg l⁻¹ and even more than 10 g l⁻¹ during storm events (Barille *et al.*, 1997). Resuspended clay and fine silt sediments from human activities such as dredging, also affect turbidity level, depending on the duration and intensity of the activity and sediment characteristics (Ryan, 1989; Yell and Riddell, 1995). Furthermore, discharges from rivers and drainage systems contribute significant loads of sediment into the estuaries and open coastal waters affecting water quality, in particular, turbidity level (Miller, 1981; Roesner, 1982; Griffiths and Gladsby, 1985; Line *et al.*, 1996). The *SPM* volume discharged by rivers ranges from very low to hundreds of tonnes per day (Griffiths and Gladsby, 1985).

High loads of suspended sediments in the water column reduce light penetration and alter radiation (Ellis, 1936). Thus, primary production can be adversely affected if resuspended sediments persist in the water column. Indeed, Sherk *et al.* (1974)

demonstrated under laboratory conditions that light attenuation caused by resuspended sediment significantly reduced the carbon assimilation of four phytoplankton species by 50-90% depending on the species and the level of *SPM*. Accordingly, populations that depend on phytoplankton as a food source could be adversely affected if resuspension persists for a long period. In addition, high resuspension may also smother benthic macrofauna if high loads of *SPM* settle out from the water column (Foster *et al.*, 1991).

Benthic macrofauna, such as suspension feeding bivalves can dominate the benthic community in the estuarine and open coastal waters. For example, on Georges Bank, West Coast Canada, scallops (*Placopecten magellanicus*) account for 85 % of the macrofaunal biomass (Thouzeau *et al.*, 1991). In the Baltic Sea, mussels (*Mytilus edulis*) totally dominate benthic animal biomass due to the exclusion of its major predators which cannot tolerate the low salinity (Kautsky and Evans, 1987). Such high densities of bivalves can remove significant amount of suspended particles, often depleting phytoplankton in the overlaying water (Wright *et al.*, 1982; Cohen *et al.*, 1984; Nichols, 1985). Because of this, bivalves are regarded as important agents of sedimentation to the benthos (Doering *et al.*, 1987; Kautsky and Evans, 1987).

Increased deposition of organic matter via seston sedimentation, may increase the return of remineralised nutrients from sediment to the water column (Kelly and Nixon, 1984). These nutrients can support a large portion of the phytoplankton demand. Consequently, benthic suspension feeders may affect populations and ecological processes in the marine ecosystem in general, not only by removing organic matter from the water column, but also through enhancing the return of nutrients (Doering *et al.*, 1987). This process is known as benthic-pelagic coupling (Pilditch, 1997).

For suspension feeders, resuspended sediment causes large variations in food quality and concentration (Anderson and Mayer, 1986; Grant *et al.*, 1997). Enhanced food sources were reported when resuspended sediment originated from high food quality sediments (Wainright, 1990), whereas dilution of organic matter or phytoplankton was reported when sediments were comprised mostly of inorganic matter (Cranford and Gordon, 1992; Grant *et al.*, 1997). However, if turbidity is above some critical level, the effect can be detrimental to suspension feeders as the filtration apparatus is clogged, inhibiting feeding and respiration (Grant and Thorpe, 1991), and harming gill tissue (Morse *et al.*, 1982).

This study focuses on the feeding behaviour of three New Zealand bivalve species; scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*), exposed to large variations in the concentration and organic content of suspended matter. Such conditions may occur as a result human activities such as dredging, as well as during natural events such as storms. Resuspended sediments may alter the food quality and quantity, and either (1) prompt compensatory feeding physiological strategies unique to different bivalve species, or (2) result in deterioration of growth if bivalves can not tolerate high sediment loads. This laboratory study was intended to determine predictive relationships between food quality and quantity and bivalve feeding behaviour and energetics, under range of conditions expected in the field.

The second part of this study examines the effects of resuspended sediments caused by dredging on seston quality (in terms of organic content and pigment concentration) and quantity. The need to quantify the effects arises from the fact that, although larger particle sizes will settle when disturbed during dredging, the fine portion

including clay and fine silt, will stay longer in the water column. Consequently, these fine sediments can be transported over considerable distances from the source (Jago *et al.* 1993) affecting water quality in neighbouring areas.

1.1 Location and Objectives of the Study

Experiments to quantify the impacts of resuspended sediment on bivalves feeding behaviour were carried out at Butters Wharf, Port of Tauranga (Fig. 1.1). The black silt/mud used in the study were obtained from the Stella Passage, and is similar to sediments described by Healy and Roberts (1997) for sites 6, and 9 in their study. Scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) commonly found at Tauranga Harbour (Park, 1991), were used in this study.

The primary objectives of this study are to:

- (1) describe the effects of sediment concentration and quality on bivalve feeding rates and energetics; and
 - (2) quantify through water sampling whether resuspended sediment created during dredging affects the seston quality and quantity at the dredge and adjacent sites.
- By seston quality is meant, the organic content and pigment (chlorophyll *a* + phaeophytin *a*) concentration.

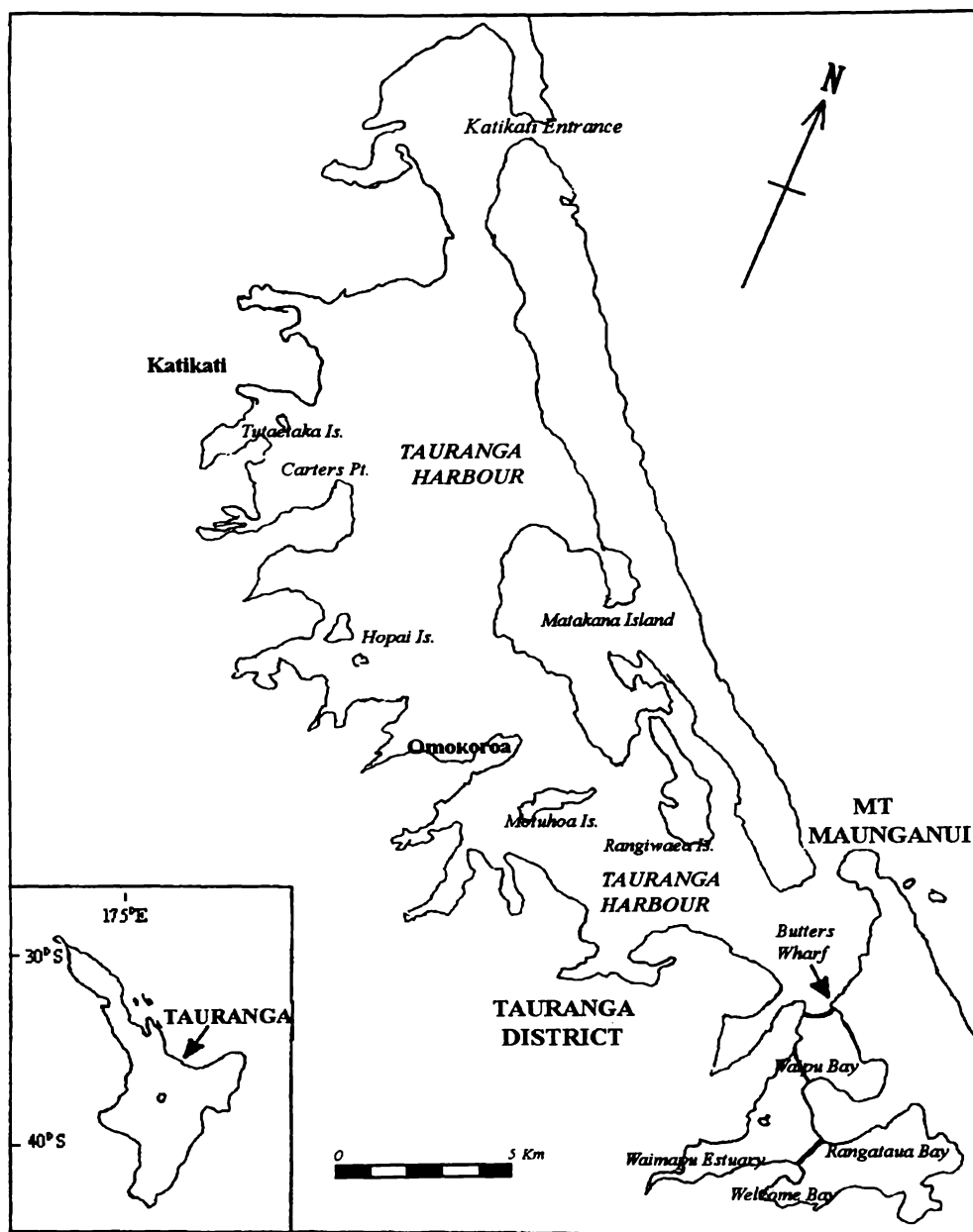


Figure 1.1 The North Island of New Zealand showing the location of Tauranga Harbour and Butters Wharf where all bivalve feeding experiments were conducted

1.2 Structure of Thesis

In order to meet the different objectives of this study, the thesis is divided into four chapters. Chapter 2 deals with the impact of resuspended sediment on bivalve feeding rates and energetics while Chapter 3 deals with the impact of resuspended sediment on seston quality and quantity during dredging operations. Conclusions and recommendations for future research are contained in Chapter 4.

CHAPTER 2

Effects of Turbidity on Bivalve Feeding Rates and Energetics

2.1 Introduction

In this chapter, the feeding rates and energetics of *Pecten novaezelandiae*, *Perna canaliculus*, and *Paphies australis*, common species in Tauranga Harbour are examined by exposing them to a range of seston concentrations. Food quality and quantity was altered by adding silt and clay particles to natural seston in order to mimic resuspension events caused by dredging or storms. The added silt and clay particles were composed of either high or low organic content. This particle size range was chosen as it is likely to stay in the water column longer, thus affecting adjacent areas once resuspended.

2.2 Review on the Effects of Turbidity on Bivalve Feeding Rates and Energetics

Resuspended sediments can be caused by natural events, human induced activities, or discharges from rivers and drainages (Miller, 1981; Roesner, 1982; Ryan 1989; Yell and Riddell, 1995; Grant *et al.*, 1997). Although large sized particles will settle out from the water column quickly, finer particles (clay and fine silt) will stay in the water column longer. Consequently, they may be carried over considerable distances, affecting the water quality in neighbouring areas (Jago *et al.*, 1993). Resuspended

sediment influences the seston quality in terms of organic and pigment content by either increasing or decreasing it, depending on the quality of the resuspended sediment itself (Wainright, 1990; Grant *et al.*, 1997).

Food concentration is a major factor influencing growth and reproduction of suspension feeding bivalves (Yukihira *et al.*, 1998ab). Relationships between food concentration and food quality versus feeding rates and energetics have been well studied (Widdows *et al.*, 1979; Bayne and Newell 1983; Cranford and Gordon, 1992; Navarro *et al.*, 1992; Hawkins and Bayne, 1992; Bayne, 1993). Yet, controversy over which feeding strategies are responsible for improved energy gain over a wide range of food concentration has not been fully appreciated. To most workers physiological compensation such as the ability to preferentially ingest organic materials through the production of pseudofaeces, regulation of clearance rates (Hawkins and Bayne, 1992; Bayne, 1993; Iglesias *et al.*, 1992; Navarro *et al.*, 1992), and alteration of metabolic activities to reduce energy expenditure (Grant and Thorpe, 1991) are important strategies for bivalves feeding upon diets with low organic content. For some, physiological compensations are denied, and responses to suspended seston are determined entirely by the physical properties of ciliary mechanisms of pumping and filtration (Jorgensen *et al.*, 1988, Jorgensen, 1990 & 1996). In these cases preferential selection does not occur (Jorgensen, 1996; Defosse and Daguzan, 1996).

Recent studies (Deslous-Paoli *et al.*, 1992; Stenton Dozey & Brown, 1992; Cranford and Hargrave, 1994; Urrutia *et al.*, 1996 & 1997; Barille *et al.*, 1997; Hawkins *et al.*, 1996 & 1998,) have observed feeding responses that maximise energy acquisition, when feeding upon high concentrations of natural seston with a low organic fraction. Urrutia *et al.*, (1997) observed a lack of reduction or slight increase in clearance rates when cockles (*Cerastoderma edule*) were exposed to a

highly turbid environment. Consequently, filtration rate (the product of clearance rates and seston concentration) increased disproportionally. This response was however, coupled with production of pseudofaeces, and therefore ingestion was regulated to some extent. Similar characteristics have also been observed for other species such as the oyster *Crassostrea gigas* (Deslous-Paoli *et al.*, 1992), the clam (*Mercenaria mercenaria*) (Stenton Dozey and Brown, 1992), the scallop (*Placopecten magellanicus*) (Cranford and Hargrave, 1994), and the mussel (*Mytilus edulis*) (Hawkins *et al.*, 1996) when exposed to short-term variations in seston concentration. These results indicated that bivalves compensated, within limits, to the dilution of food matter by pre-ingestive rejection of unwanted materials through pseudofaeces production, thereby preferentially retaining organic matter for ingestion (Hawkins *et al.*, 1996). Together with faster clearance rate, growth is maintained or enhanced to some extent.

Epifauna and infauna bivalve species also display different feeding responses to varying concentration of suspended particles (Shumway *et al.*, 1985; Hawkins and Bayne, 1992; Bacon *et al.*, 1998). For instance, epifaunal bivalves, such as scallops (*P. magellanicus*) (Bacon *et al.*, 1998) and mussels (*M. edulis*) (Hawkins and Bayne, 1992), which live a few centimetres above the substrate, regulated ingestion by decreasing clearance rates and increasing pseudofaeces production when exposed to increasing suspended sediment concentration. An infaunal clam (*Mya arenaria*), which lives in direct contact with flows very near to the bottom, regulates ingestion by reducing clearance rate but maintaining low volume of pseudofaeces produced (Bacon *et al.*, 1998). Thus, the ecological distribution of bivalve species and seston characteristics to which they are exposed maybe correspondingly reflected in their feeding responses (Yukihira *et al.*, 1998b). These strategies may have been developed

as adaptive features to counteract the depressing effect low food quality during resuspension events (Kiorboe and Mohlenberg, 1981).

High densities of bivalves species, such as in aquaculture areas (Kaspar *et al.*, 1985), on sand banks (Thouzeau *et al.*, 1991), estuarine areas (Kuenzler 1961), or in places like the blackish Baltic Sea (Kautsky and Evans, 1987) are able to deplete the water mass of plankton, both within the benthic boundary layer as well as in an entire coastal embayment. This possibly lead to eutrophication control (Officer *et al.*, 1982), nutrient depletion in aquaculture areas (Kaspar *et al.*, 1985), and increase in the deposition of organic matter (Doering *et al.*, 1987). Indeed, the increase of organic deposition may increased the return of remineralised nutrient to the water column, supporting a large portion of phytoplankton demand (Doering *et al.*, 1987). Thus, these bivalves can influence primary production and ultimately the production of pelagic consumers (Kelly and Nixon., 1984; Doering *et al.*, 1987; Alpine and Cloern, 1992).

2.3 General Ecology of Scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*)

Pecten novaezelandiae are epifauna and are found on substrates ranging from fine gravel to muddy sand (Morton and Miller, 1973; Bull, 1976). Bull (1976) reported that *P. novaezelandiae* are found on soft mud in Pelrous Sound, New Zealand, and are even found in some of the more sheltered bays (eg Miro Bay, New Zealand) where silt accumulates rapidly. *Perna canaliculus*, the greenshell mussel, is also epifaunate, and grow naturally on sandy bottoms in deeper water and in the lower intertidal and sublittoral zones of coastal shores (Paine 1971; Morton and Miller, 1973). *Paphies*

australis, on the other hand is an infaunal species inhabiting mostly sandflats within estuarine shores (Caroll and Wells, 1995), and the dynamic regions of harbour entrances (Hooker, 1995; Hull 1996). The seston characteristics in open coastal waters and estuaries vary greatly depending on meteorological and tidal conditions (Fegley *et al.*, 1992; Grant *et al.*, 1997; Yukihiro *et al.*, 1998). Consequently, these bivalves species may possess different feeding responses as adaptive features to counteract the effects of resuspension on seston quality.

2.4 Methods and Materials

2.4.1 Feeding Experiments

Experiments were performed at the field laboratory, Butters Wharf, Port of Tauranga, during May and September 1998. Bivalves species *Pecten novaezelandiae*, *Perna canaliculus* and *Paphies australis* used in the experiments were collected from a natural population sited within Tauranga Harbour, and placed in a submerged cage at the wharf two weeks prior to each experiment. In experiment 1, the species were exposed to non-ashed clay/silt sediments (organic content 22.1 ± 2.6 %) ranging from 20 to 300 mg l⁻¹ added to natural seston. In experiment 2, ashed sediments (organic content 0.02 ± 0.01 %) were used but with narrower range of concentrations, 5 to 150 mg l⁻¹ (Table 2.1, 2.2, 2.3). To provide a direct comparison of feeding responses to ashed and non-ashed sediments, non-ashed treatment (20 mg l⁻¹ + natural seston) was used during experiment 2.

Table 2.1 *Pecten novaezelandiae*. Mean concentrations of total particulate matter (*TPM*), total pigment, and particulate organic matter (*POM*) fraction of diet (ashed or non-ashed sediments + natural seston), and mean concentration of natural *TPM* and *POM* fraction used in the diet mixture. Temperature ranges recorded during the experiments are also shown

SCALLOP (<i>P. novaezelandiae</i>)						
EXPERIMENT 1 (May 1998) Non-ashed sediment						
Component	TPM	TPM	POM	POM	Total pigment	Temperature
Source	diet	natural	diet	natural	diet	
	(mg l ⁻¹)	(mg l ⁻¹)	(fraction)	(fraction)	(µg mg ⁻¹)	°C
1. Natural seston (mean ± sd)	12.2 ± 5.6	12.4 ± 6.2	0.29 ± 0.13	0.29 ± 0.11	122.0 ± 32.1	15.0 - 16.6
2. Natural seston + 20 mg l ⁻¹ (mean ± sd)	39.3 ± 8.9	15.5 ± 4.4	0.17 ± 0.04	0.27 ± 0.03	81.5 ± 23.7	14.6 - 17.7
3. Natural seston + 60 mg l ⁻¹ (mean ± sd)	82.2 ± 10.5	10.3 ± 3.5	0.14 ± 0.02	0.31 ± 0.08	47.6 ± 11.4	15.3 - 16.3
4. Natural seston + 150 mg l ⁻¹ (mean ± sd)	205.3 ± 27.6	33.2 ± 18.8	0.10 ± 0.01	0.20 ± 0.05	29.2 ± 15.8	14.9 - 16.9
5. Natural seston + 600 mg l ⁻¹ (mean ± sd)	733.3 ± 164.7	36.1 ± 12.3	0.10 ± 0.01	0.22 ± 0.05	17.5 ± 8.7	15.0 - 17.2
EXPERIMENT 2 (September 1998) Ashed sediments						
1. Natural seston (mean ± sd)	26.3 ± 24.7	26.3 ± 24.7	0.33 ± 0.14	0.33 ± 0.14	75.2 ± 23.4	15.3 - 16.4
2. Natural seston + 5 mg l ⁻¹ (mean ± sd)	60.5 ± 55.8	55.5 ± 55.8	0.17 ± 0.04	0.20 ± 0.06	36.3 ± 6.68	15.0 - 16.9
3. Natural seston + 20 mg l ⁻¹ (mean ± sd)	48.6 ± 11.4	28.6 ± 11.4	0.12 ± 0.02	0.21 ± 0.04	52.6 ± 20.4	15.4 - 15.9
4. Natural seston + 60 mg l ⁻¹ (mean ± sd)	96.5 ± 11.08	36.5 ± 11.08	0.09 ± 0.02	0.25 ± 0.04	25.3 ± 6.9	14.5 - 16.9
5. Natural seston + 150 mg l ⁻¹ (mean ± sd)	191.3 ± 13.0	41.03 ± 13.0	0.07 ± 0.04	0.32 ± 0.02	9.3 ± 2.5	14.6 - 17.0

Table 2.2 *Perna canaliculus*. Mean concentrations of total particulate matter (*TPM*), total pigment, and particulate organic matter (*POM*) fraction of diet (ashed or non-ashed sediments + natural seston), and mean concentration of natural *TPM* and *POM* fraction used in the diet mixture. Temperature ranges recorded during the experiments are also shown

MUSSEL (<i>P. canaliculus</i>)						
EXPERIMENT 1 (May 1998) Non-ashed sediment						
Component Source	TPM diet (mg l ⁻¹)	TPM natural (mg l ⁻¹)	POM diet (fraction)	POM natural (fraction)	Total pigment diet (µg mg ⁻¹)	Temperature °C
1. Natural seston (mean ± sd)	13.0 ± 7.0	13.4 ± 7.4	0.28 ± 0.09	0.28 ± 0.08	116.3 ± 51.6	15.1 – 17.4
2. Natural seston + 20 mg l ⁻¹ (mean ± sd)	43.9 ± 10.6	21.0 ± 11.1	0.16 ± 0.04	0.25 ± 0.09	60.4 ± 17.7	15.0 – 16.9
3. Natural seston + 60 mg l ⁻¹ (mean ± sd)	90.1 ± 13.2	25.4 ± 14.7	0.12 ± 0.01	0.23 ± 0.05	46.0 ± 13.5	14.9 – 16.9
4. Natural seston + 150 mg l ⁻¹ (mean ± sd)	176.4 ± 13.4	27.9 ± 27.9	0.11 ± 0.01	0.23 ± 0.04	29.0 ± 8.5	14.9 – 17.0
5. Natural seston + 300 mg l ⁻¹ (mean ± sd)	331.5 ± 32.1	56.3 ± 41.5	0.10 ± 0.02	0.19 ± 0.09	18.8 ± 6.4	15.3 – 17.1
EXPERIMENT 2 (September 1998) Ashed sediments						
1. Natural seston (mean ± sd)	48.2 ± 23.2	48.2 ± 23.2	0.15 ± 0.04	0.15 ± 0.05	61.3 ± 29.4	15.6 – 15.9
2. Natural seston + 5 mg l ⁻¹ (mean ± sd)	41.6 ± 16.3	36.6 ± 16.3	0.19 ± 0.03	0.22 ± 0.05	41.0 ± 6.4	13.4 – 15.5
3. Natural seston + 20 mg l ⁻¹ (mean ± sd)	43.8 ± 7.5	23.8 ± 7.5	0.12 ± 0.02	0.22 ± 0.04	29.2 ± 11.1	15.6 – 16.9
4. Natural seston + 60 mg l ⁻¹ (mean ± sd)	112.6 ± 22.7	52.6 ± 22.7	0.11 ± 0.02	0.26 ± 0.12	16.4 ± 6.3	15.3 – 15.9
5. Natural seston + 150 mg l ⁻¹ (mean ± sd)	194.5 ± 24.7	44.5 ± 24.7	0.05 ± 0.01	0.29 ± 0.19	12.0 ± 1.9	15.6 – 16.5

Table 2.3 *Paphies australis*. Mean concentrations of total particulate organic matter (*TPM*), total pigment, and particulate organic matter (*POM*) fraction of diet (ashed or non-ashed sediments + natural seston), and mean concentration of natural *TPM* and *POM* fraction used in the diet mixture. Temperature ranges recorded during the experiments are also shown

PIPI (<i>P. australis</i>)						
EXPERIMENT 1. (May 1998) Non-ashed sediment						
Component Source	TPM diet (mg l ⁻¹)	TPM natural (mg l ⁻¹)	POM diet (fraction)	POM natural (fraction)	Total pigment diet (µg mg ⁻¹)	Temperature °C
1. Natural seston (mean ± sd)	39.0 ± 23.8	39.0 ± 23.8	0.26 ± 0.20	0.26 ± 0.20	105.0 ± 39.8	14.6 – 17.0
2. Natural seston + 20 mg l ⁻¹ (mean ± sd)	46.8 ± 15.0	26.7 ± 14.9	0.15 ± 0.02	0.24 ± 0.10	68.5 ± 16.7	15.0 – 17.1
3. Natural seston + 60 mg l ⁻¹ (mean ± sd)	77.1 ± 11.4	18.8 ± 9.2	0.15 ± 0.02	0.17 ± 0.12	35.8 ± 9.4	14.3 – 16.9
4. Natural seston + 150 mg l ⁻¹ (mean ± sd)	176.7 ± 17.0	25.8 ± 14.4	0.12 ± 0.04	0.23 ± 0.10	29.1 ± 9.8	15.3 – 17.0
5. Natural seston + 300 mg l ⁻¹ (mean ± sd)	322.2 ± 19.6	13.7 ± 11.6	0.11 ± 0.04	0.21 ± 0.06	22.9 ± 8.8	15.2 – 17.3
EXPERIMENT 2 (September 1998) Ashed sediments						
1. Natural seston (mean ± sd)	47.4 ± 35.1	47.4 ± 35.1	0.22 ± 0.05	0.22 ± 0.05	53.2 ± 18.0	15.1 – 15.9
2. Natural seston + 5 mg l ⁻¹ (mean ± sd)	20.1 ± 3.6	15.1 ± 3.6	0.20 ± 0.03	0.27 ± 0.03	86.2 ± 28.0	14.6 – 17.3
3. Natural seston + 20 mg l ⁻¹ (mean ± sd)	58.0 ± 32.1	38.0 ± 32.1	0.13 ± 0.02	0.24 ± 0.08	28.2 ± 9.0	15.6 – 18.9
4. Natural seston + 60 mg l ⁻¹ (mean ± sd)	124.4 ± 58.7	64.37 ± 58.7	0.07 ± 0.02	0.20 ± 0.08	24.2 ± 5.5	14.0 – 15.3
5. Natural seston + 150 mg l ⁻¹ (mean ± sd)	178.0 ± 11.5	28.0 ± 11.5	0.03 ± 0.01	0.27 ± 0.11	11.5 ± 1.5	13.8 – 16.3

Clay and silt used in the experiments was obtained after sieving sediment collected from Stella Passage through a 65 μm mesh sieve. According to Healy and Roberts (1997), the accumulated black silt/mud sediment within the Passage had relatively low concentrations of heavy metals, but had high organic fraction. The clay/silt fraction was preserved by drying at 100 °C overnight. Its organic content was 22.1 (\pm 2.6) % and total pigment was 25.7 (\pm 0.9) $\mu\text{g mg}^{-1}$. Prior to experiment 2, the sediment was combusted at 500 °C overnight, ensuing a very low organic content (0.02% \pm 0.01%) and total pigment (0.16 \pm 0.02 $\mu\text{g mg}^{-1}$) content.

Twelve to fourteen hours prior to each feeding experiment *Pecten novaezelandiae*, *Perna canaliculus*, or *Paphies australis* (depending on the random order of bivalve species) were starved in a closed circulation system containing aerated filtered seawater to provide a standardised hunger. The temperature of the system was maintained constant at ambient levels (Table 2.1, 2.2 and 2.3).

After the starvation period, 'healthy' bivalves as depicted by sufficient gaping were placed in flow through feeding chambers (18.5 cm length by 13 cm width and volume of 1.6 l). The inflow port of the chamber consisted of an upward curved tygon plastic tube mounted at the inflow port and an horizontal slot placed after the water current reached the animal, to minimise turbulence across the bottom (Iglesias *et al.*, 1998). The purpose of the slot was to prevent biodeposits from being washed out through the outflow port (Fig. 2.1).

The diet mixtures (silt and clay + natural seston) selected in random order were directly pumped from a header tank to eight feeding chambers at flow rates between 160 and 190 ml min^{-1} (Fig 2.2) The diet mixture were kept in suspension by an electrical

stirrer. Each experiment commenced when bivalves began feeding as indicated by sufficient shell gaping, and lasted for 8 hours. Seven feeding chambers held live specimens, one animal for *Pecten novaezelandiae*, and *Perna canaliculus*, and two for *Paphies australis* due to their smaller size and lower feeding rate. The eighth chamber held an empty shell to correct for sedimentation (Iglesias *et al.*, 1998).

Food concentration, organic and total pigment content of diets were determined every two hours from the header tank. Three replicate of water samples were filtered onto ashed and pre-weighed 45 mm Whatman GFC filters, rinsed with isotonic ammonium formate to dissolve salts, dried in an oven at 80°C for 24 hours, weighed to give total particulate matter (*TPM*, mg l⁻¹) concentration, and then combusted in a furnace at 480°C for 12 hours before reweighing to give particulate inorganic matter (*PIM*, mg l⁻¹) concentration. Particulate organic matter (*POM*, mg l⁻¹) represented the difference between *TPM* and *PIM*. Total pigment (chlorophyll *a* and pheophytin *a*) were determined by fluorometric procedures according to Arar and Collins (1997) on three replicates.

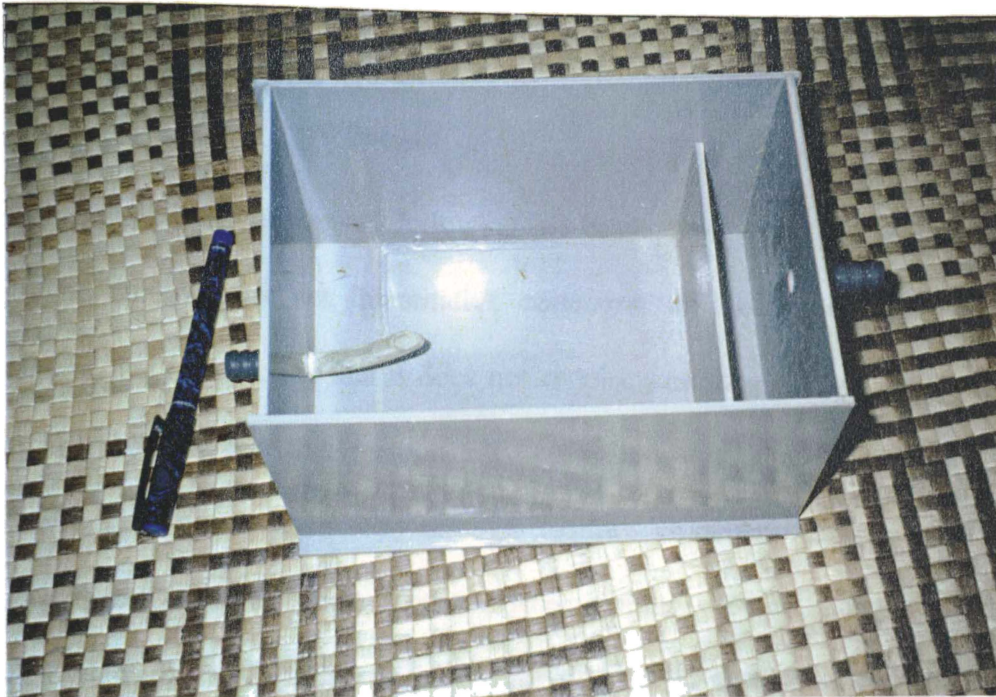


Figure 2.1 Feeding chamber used in the experiments

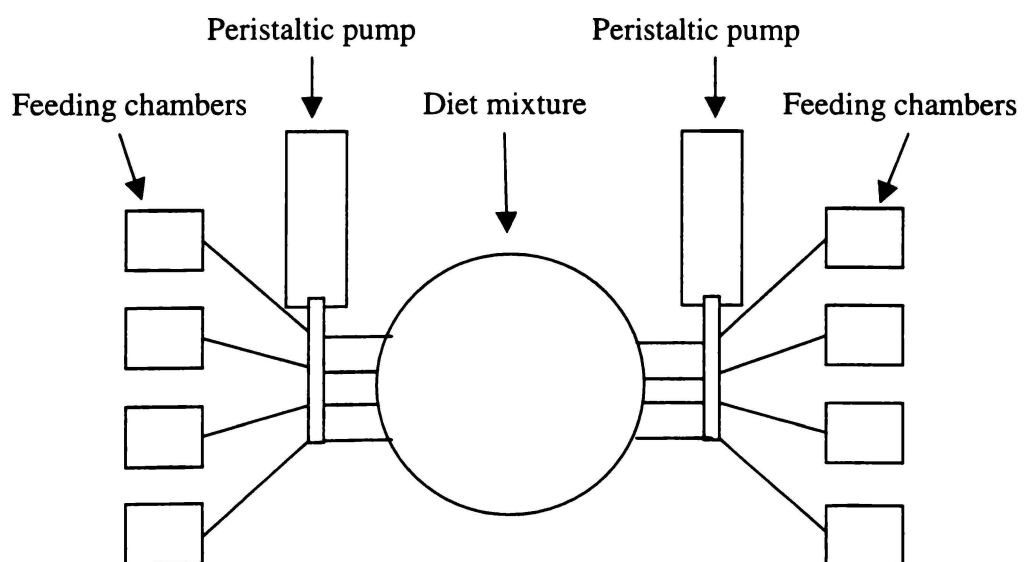


Figure 2.2 Schematic drawing of the equipment used during the feeding experiment

2.4.2. Calculation of Feeding Rates

The feeding rates were determined following the biodeposition method of Iglesias *et al.* (1992). The method involves quantitative collection of biodeposition produced. An advantage of this approach is that it does not require sampling of the outflow from the feeding chambers. When this method was compared with the depletion in particle concentrations in an open or flow-through feeding chamber, Iglesias *et al.* (1998) concluded that results from both methods were similar. Indeed, comparison of both methods by Urrutia *et al.* (1996) revealed a high degree of correspondence on clearance rate between estimates from both methods, with coefficient of determination of 0.86.

The method assumes that the *POM:PIM* ratio is the same for particles captured by the bivalves gill and for particles sampled in the water column. The values for feeding rates as estimated according to the procedures outlined below assumed all particles are retained with 100% efficiency. No previous work has evaluated retention efficiencies for the species used in this study, however, previous studies have shown that mussels, *Mytilus edulis* (Lucas *et al.*, 1987), retained particles >4 µm with 100% efficiency whereas the retention efficiency for the scallop *Placopecten magellanicus* (Cranford and Gordon, 1992) decreases progressively from 95% at 8 µm to 15% at 2 µm. The bulk of sediments used in this study consisted of silt/clay, <33% non-ashed and <26% ashed sediments were less than 4 µm (Appendix A.1 and A.2).

Faeces and pseudofaeces were collected and then separated at the end of each experiment. Where possible two aliquots of biodeposits were separated for the determination of organic and total pigment content. This separation was taken into

account when calculating the total biodeposition production rate, organic, inorganic and total pigment concentrations. In addition, when separating biodeposits from deposited sediment was physically impossible, materials in control chambers was collected and treated in the same way as the biodeposits to obtain a quantitative reference of sedimentation (Iglesias *et al.*, 1998).

Pseudofaeces (RR , mg h^{-1}) and egestion (ER , mg h^{-1}) production rates were determined by weighing after both were filtered and dried at 80°C for 24 hours. The weight established after combusting at 480°C for 12 hours gave the inorganic content of pseudofaeces (IRR , mg h^{-1}) and faeces (IER , mg h^{-1}). Whereas the organic content of pseudofaeces (ORR , mg h^{-1}) and faeces (OER , mg h^{-1}) represented the difference between the biodeposition production rates (RR and ER) and inorganic content (IRR and IER). Total pigment (chlorophyll *a* and pheophytin *a*) were determined by fluorometric procedures according to Arar and Collins (1997).

Based on the assumption that absorption of inorganic matter by bivalves is negligible (Conover, 1966), the sum of IRR and IER equalled the amount of inorganic filtered (IFR , mg h^{-1}) from suspension. From the rate of inorganic filtration, and the PIM concentration in the diets, the clearance rates (CR , l h^{-1}) were calculated (Iglesias *et al.*, 1992, 1996; Urrutia *et al.*, 1996) as:

$$CR = \frac{IFR}{PIM} \quad (2.1)$$

Filtration rate (FR , mg h^{-1}) for TPM was calculated as:

$$FR = CR \times TPM \quad (2.2)$$

Similarly, filtration rate for organic matter (OFR , mg h^{-1}) was estimated as:

$$OFR = CR \times POM \quad (2.3)$$

Total ingestion rate (IR , mg h^{-1}) represents the amount of food actually ingested by the animal and it was estimated by:

$$IR = FR - RR \quad (2.4)$$

and organic ingestion rate as (OIR , mg h^{-1}) was estimated as:

$$OIR = OFR - ORR \quad (2.5)$$

2.4.3. Selection Efficiency

Selection of high quality food particles was measured by the difference in POM in pseudofaeces relative to that in the food (Navarro *et al.*, 1992). If POM in pseudofaeces was lower than in food then selection has occurred, yet this estimate only represents a qualitative measurement of selection (Ward and MacDonald, 1996; Bacon *et al.*, 1998). Ward and MacDonald (1996) introduced the compensation index (CI), a term which expresses the fraction of organic ingested matter assumed to have been selected relative to diet organic fraction. A positive result signifies that a bivalve has altered the ingested organic fraction by pre-ingestive selection through pseudofaeces production. CI is calculated as:

$$CI = \frac{IOF - DOF}{DOF} \quad (2.6)$$

where *IOF* is the ingested organic fraction and *DOF* is the diet organic fraction. Similarly, *CI* for total pigment was also estimated using the same equation (2.6) but total pigment was used instead of organic fraction, i.e:

$$CI = \frac{IR_{total\ pigment} - Diet_{total\ pigment}}{Diet_{total\ pigment}} \quad (2.7)$$

where *IR_{total pigment}*, the relative quantity of total pigment ingested ($\mu\text{g mg}^{-1}$) is estimated from:

$$IR_{total\ pigment} = \frac{(Diet_{total\ pigment} \times FR) - (PSF_{total\ pigment} \times RR)}{IR} \quad (2.8)$$

where *Diet_{total pigment}*, is the total pigment contained in the food; *PSF_{total pigment}* is the total pigment in the pseudofaeces; *FR*, *RR*, and *IR* are the same as those designated above. Similarly, this method gives a more realistic estimate of selection to the net energy balance of the feeding bivalves, as it considers the rate of total pigment cleared from seston and rejected in pseudofaeces compared to the total amount of pigment ingested per unit time.

2.4.4 Bivalve Energetics

Scope for growth (SFG ; $J\ h^{-1}\ g^{-1}$) represents the amount of energy available to bivalves for growth and reproduction after maintenance requirements are met. It was estimated by:

$$SFG = AB - (R + U) \quad (2.9)$$

where AB is the absorbed ration, R is the energy loss due respiration, and U is the energy loss due to ammonia excretion (Widdows, 1985).

Ammonium excretion rates were not measured, therefore values of the SFG calculated from the difference between absorbed ration and respiratory loss would be a slight over-estimate of the true SFG (Bayne and Newell, 1983 & Navarro *et al.*, 1991). Excretory losses are considered negligible, they only represent a small fraction of losses when compared to respiratory losses (Bayne and Newell, 1983).

SFG is an energy measurement, therefore all estimates of absorption rates and oxygen consumption were converted to joules assuming 1 mg organic matter = 20.78 J, and 1 ml O_2 = 20.36 J (Crisp, 1971).

Organic absorption rates (OAR ; $mg\ h^{-1}$) represent the amount of organic material absorbed per unit time, by bivalves across the gut, and was estimated as (Iglesias *et al.* 1996):

$$OAR = OIR - OER \quad (2.10)$$

where *OIR* is the organic ingestion rates, and *OER* is the organic egestion rate

Absorption efficiency (*AE*) was estimated by:

$$AE = \frac{OAR}{OIR} \quad (2.11)$$

Respiration rates ($\text{ml O}_2 \text{ h}^{-1} \text{ g}^{-1}$) were estimated following the procedures of Pilditch (1997). At the conclusion of each feeding experiment, four bivalves were transferred to individual respiration chambers containing 2.5 to 3.0 l of the experimental diets, with a fifth chamber containing empty shells to account for bacterial respiration. Chambers were placed in a water bath maintained at ambient temperature and incubated in the dark. Throughout the incubation period, the water in the chamber was circulated from above with a magnetically driven impeller. After an acclimation period of 30 minutes, water samples were collected in BOD bottles by gently pressing down the 'o'-ring sealed lid into the chamber forcing out water through a sampling port, where oxygen concentration was measured with an Omega PHH71 DO_2 meter. A second reading was taken 1 hour later. If oxygen depletion was <10%, another reading was taken 30 minutes later. The oxygen consumption rate (VO_2 , $\text{ml O}_2 \text{ h}^{-1}$) was computed according to Pilditch (1997) as:

$$[O_2]_{\text{initial}} - [O_2]_{\text{final}} = \text{VO}_2 \times \sum_{i=1}^i \frac{(t_{i+1}) - t_i}{V_i} \quad (2.12)$$

where $[O_2]_{initial}$ is the initial oxygen concentration, $[O_2]_{final}$ is the final oxygen concentration, t_i is the time between successive O_2 measurements, and V_i is the chamber volume when the measurement was taken.

2.4.5 Standardisation of Physiological Rates

At the conclusion of each experiment, all bivalve species were excised and kept in a freezer until they were oven dried at 90 °C for 72 h then weighed. To reduce potential variation in feeding and energetic rate estimates that may arise due to differences in body size, rates were standardised to an equivalent of 1 gram dry tissue weight using the formula

$$Y_s = Y_e \times \left(\frac{W_s}{W_e} \right)^b \quad (2.13)$$

where Y_s = standardised physiological measurement, Y_e = uncorrected physiological measurement, W_s = standardised weight of animal, W_e = the observed weight of the animal and b is the weight exponent for the physiological rate function. A weight function of 0.68 was used for clearance and rejection rates in this study. Similarly, metabolic rates were also standardised to 1 gram dry tissue weight but with a weight exponent of 0.76 used for all species. Both of these weight exponent functions were similar to values published on other species (Bacon *et al.* 1998).

2.4.6. Statistical Analysis

To determine whether the feeding behaviour of bivalves varied with diet concentrations, a set of regressions were fitted to experimental data, following standard least squares procedures using Minitab version 10.5. Regression analyses were performed according to the functional relationships listed in Table 2.4. The ANOVA test ($\alpha = 0.05$) was performed on the regression functions. A significant ANOVA indicated that the changes in total particulate matter explained variation in feeding rates and energetics. The functions with highest r^2 was accepted as the one that best explained the relationship between seston concentration and the dependent variable (Harraway, 1995).

A student *t*-test was used to determine if compensation indices (*CI*) were significantly different from zero. If the data deviated from normality, a non-parametric Wilcoxon rank test was used (Zar, 1996).

One way ANOVA ($\alpha = 0.05$) was used to determine if *TPM* concentrations and *POM* contents (20 mg l⁻¹ ashed or non-ashed sediment + to natural seston) were significantly different from one another within each species. Also, a one-way was employed to determine if the feeding rate and energetic were significantly different between the diet mixtures within each bivalve species.

Table 2.4 Functional relationships used to described the feeding physiology and energetic data

Regression Description	Formula
simple linear	$y = b + mx$
polynomial	$y = b + m_1x_1 + m_2x_2^2 + m_nx_n^n$
logarithmic	$y = b + m\log x$
exponential	$y = b^{mx}$
b is a constant value	
m is a coefficient corresponding to each x value	
x is seston concentration	
y is a dependent variable	

2.5 Results

2.5.1 Experimental Diets

Natural *TPM* to which clay and silt was added ranged between (mean \pm 1 SD) 10.3 ± 3.5 to 56.3 ± 41.5 mg l⁻¹, and 13.2 ± 3.8 to 64.37 ± 58.7 mg l⁻¹ during experiment 1 and 2 respectively. Despite the variation in natural seston, Tables 2.1, 2.2 and 2.3 indicate a progressive decrease in the *POM* fraction and total pigment concentrations with increasing concentrations of *TPM*. The reduction in *POM* fraction and total pigment concentration was greater when ashed sediments were added to natural seston. The temperature ranged between 14.3 – 17.7 and 13.8 – 18.9 °C for experiments 1 and 2 respectively.

2.5.2 Comparison of Feeding Physiology and Energetics Between Experiment 1 and 2 for Individual Species

2.5.2.1 Feeding Rates of Scallops (*Pecten novaezelandiae*)

Figure 2.3a illustrates the relationship between clearance rate (*CR*) to increasing levels of *TPM*, as best described by logarithmic and polynomial functions for experiment 1 and 2 respectively (Table 2.5). In experiment 1 *CR* displayed maximum values when *TPM* was $82.2 (\pm 10.5)$ mg l⁻¹ before declining to $0.03 (\pm 0.009)$ l h⁻¹ g⁻¹ when *TPM* reached $205.3 (\pm 27.6)$ mg l⁻¹. Difficulties encountered with sampling during this experiment did not allow the determination of *CR*, other feeding rates, and corresponding energy budgets at lower diet concentrations. However, *CR* observed in

experiment 2 displayed a positive increase to a maximum *CR* recorded when *TPM* concentration was $96.5 (\pm 11.08) \text{ mg l}^{-1}$ before decreasing with further increases in *TPM* concentration.

The relationships between rejection rate (*RR*), i.e pseudofaecal production, and *TPM* were best expressed by logarithmic functions for both experiments (Table 2.5). In experiment 1, *RR* decrease from $19.29 (\pm 6.86) \text{ mg h}^{-1} \text{ g}^{-1}$ to $5.92 (\pm 2.03) \text{ mg h}^{-1} \text{ g}^{-1}$ when *TPM* concentrations increased from $82.2 (\pm 10.5) \text{ mg l}^{-1}$ to $205.3 (\pm 27.6) \text{ mg l}^{-1}$. Inversely, during experiment 2 *RR* increased at a decreasing rate (Fig 2.3b). *RR* increased from $9.84 (\pm 3.69) \text{ mg h}^{-1} \text{ g}^{-1}$ to $58.28 (\pm 44.21) \text{ mg h}^{-1} \text{ g}^{-1}$ when *TPM* concentration increased from $60.5 (\pm 55.8) \text{ mg l}^{-1}$ to $191.3 (\pm 13.0) \text{ mg l}^{-1}$. In addition, scallops have the capacity to modify the quality of the ingested matter by rejecting proportionately less organic particles in pseudofaeces relative to that in diet (Fig 2.4a and 2.5a). Furthermore, the compensation index (Table 2.6) indicated that scallops produced a sufficient quantity of pseudofaeces to significantly increase the ingested organic fraction when the *POM* fraction of diet was diluted to an average of $0.14 (\pm 0.02)$ when *TPM* concentration was $82.2 (\pm 10.5) \text{ mg l}^{-1}$ in experiment 1, and to $\leq 0.12 (\pm 0.02)$ at $48.6 (\pm 11.4) \text{ mg l}^{-1}$ *TPM* concentration in experiment 2. On the contrary, scallops were unable to increased the quality of total pigment ingested as indicated by non significant *CI*.

Despite the decrease in *CR* and the concurrent increase in *RR* when *TPM* increased beyond $96.5 (\pm 11.08) \text{ mg l}^{-1}$ in experiment 2, the estimated ingestion rates (*IR*) (Fig 2.3c) actually increased from $9.88 (\pm 0.97) \text{ mg h}^{-1} \text{ g}^{-1}$ to $10.99 (\pm 0.97) \text{ mg h}^{-1} \text{ g}^{-1}$ as *TPM* concentrations increased from $96.5 (\pm 11.08) \text{ mg l}^{-1}$ to $191.3 (\pm 13.0) \text{ mg l}^{-1}$. In experiment 1, negative ingestion rate was attained when *TPM* increased beyond $82.2 (\pm 10.5) \text{ mg l}^{-1}$.

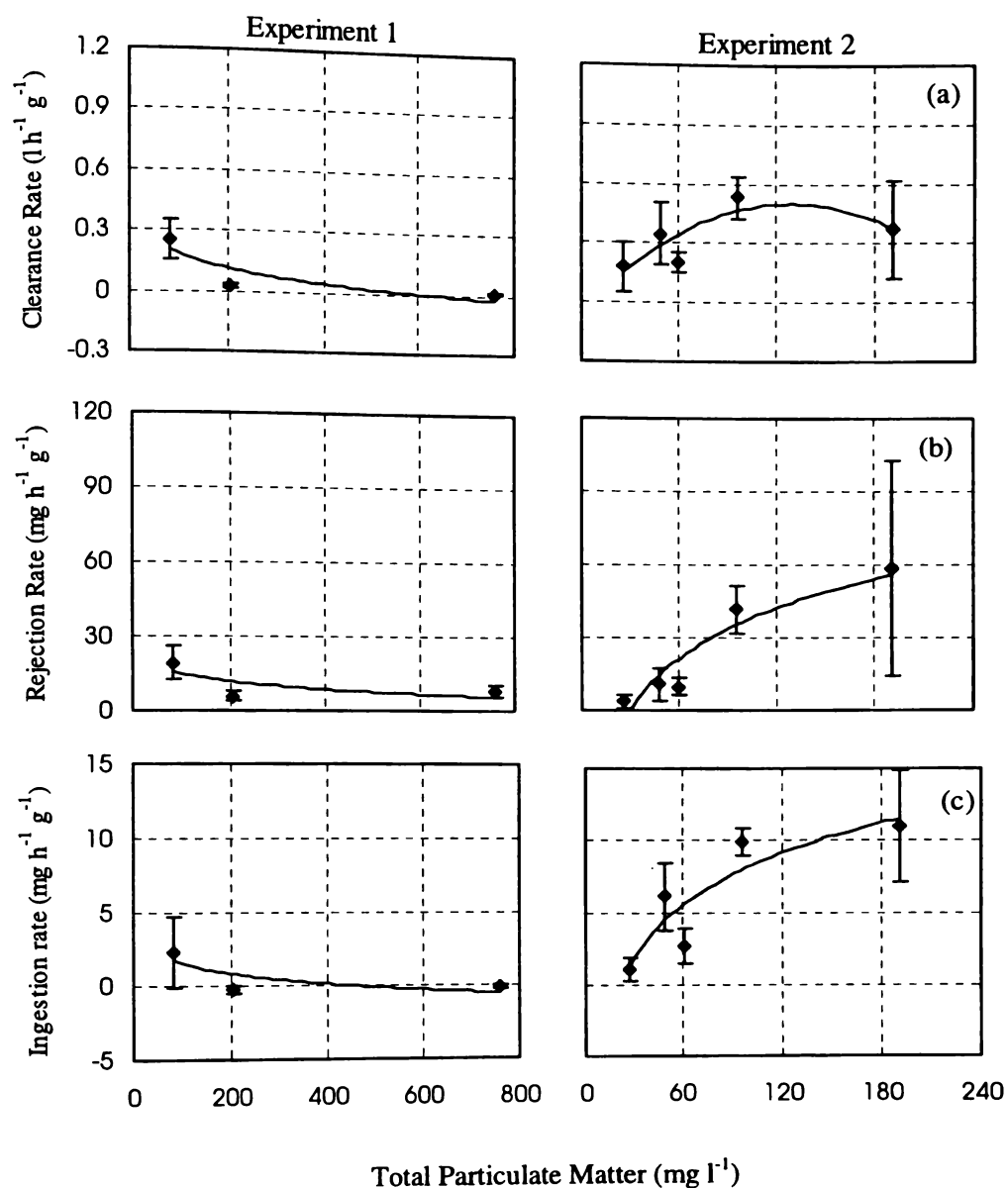


Figure 2.3 *Pecten novaezelandiae*. (a) Clearance (b) rejection and (c) ingestion rates standardised to 1 g tissue weight for scallops, exposed to different concentrations of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data represent the mean of 7 replicates

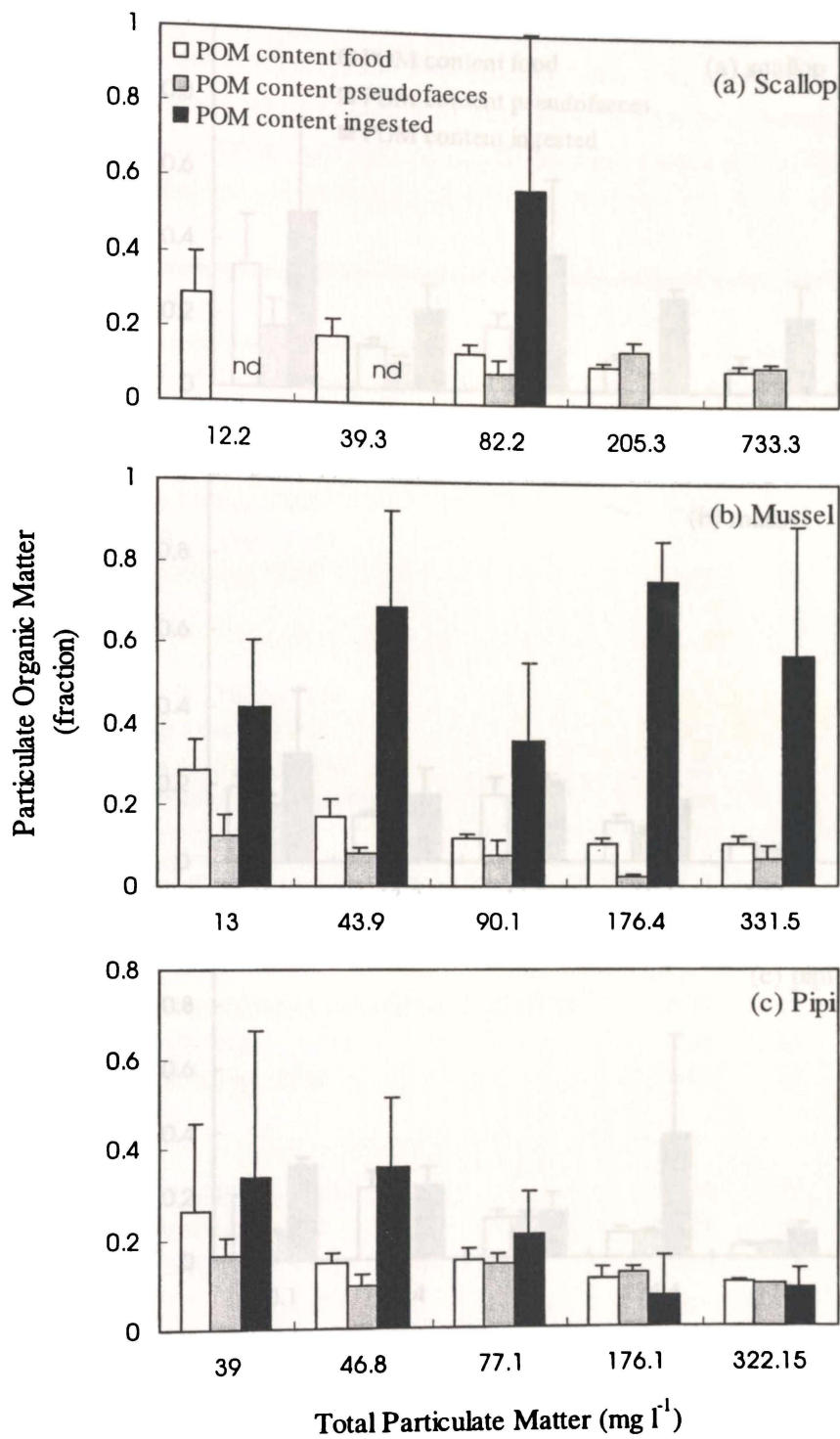


Figure 2.4 Comparison of organic fraction in the diet, pseudofaeces, and ingested matter (± 1 SD) of scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) exposed to non-ashed sediments added to natural seston during experiment 1. Data are the mean of 12 replicates for diets and 7 replicates for pseudofaeces and ingested organic fraction. Note: nd referred to no data

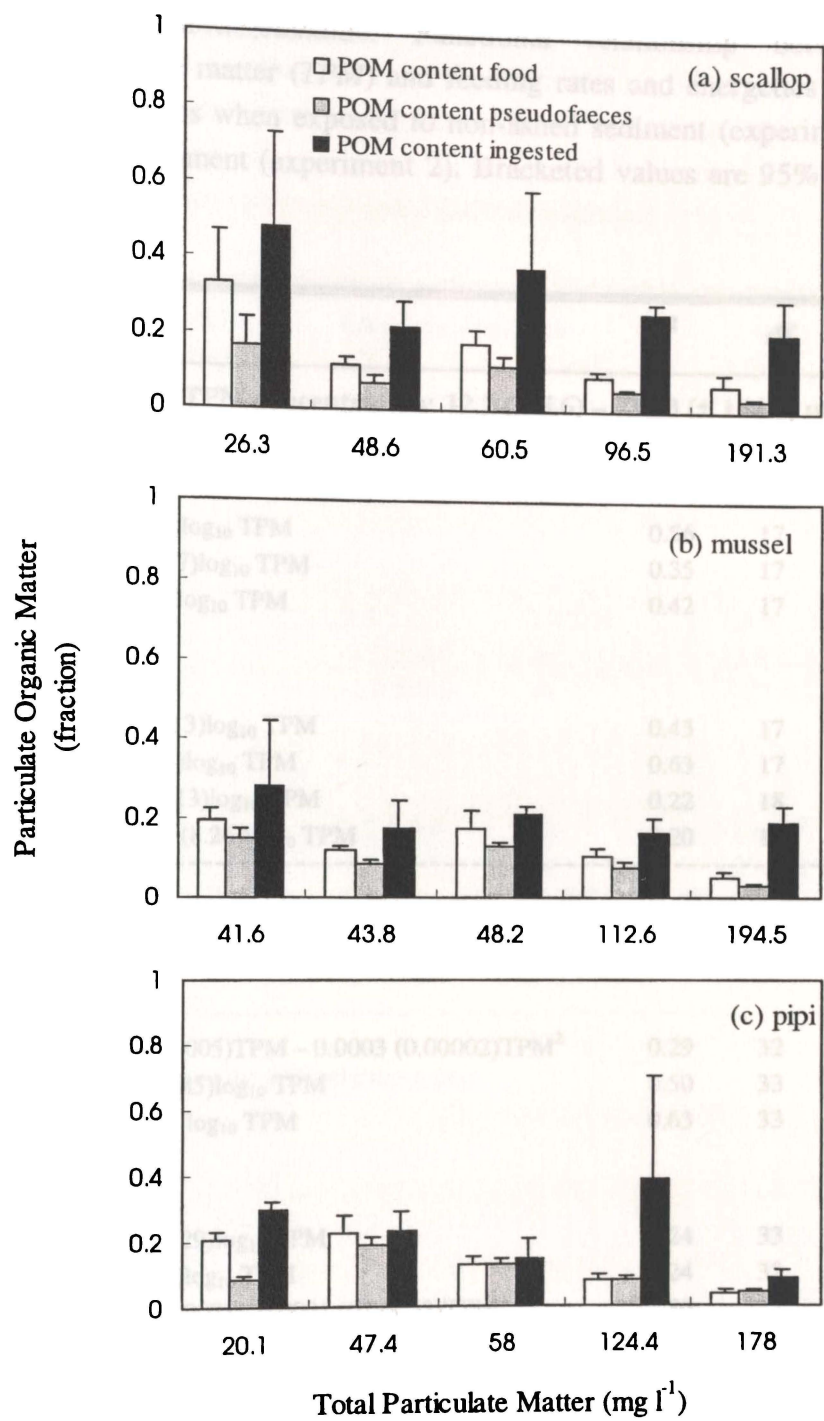


Figure 2.5 Comparison of organic fraction in the diet, pseudofaeces, and ingested matter (± 1 SD) of scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) exposed to ashed sediments added to natural seston during experiment 1. Data are the mean of 12 replicates for diets and 7 replicates for pseudofaeces and ingested organic fraction.

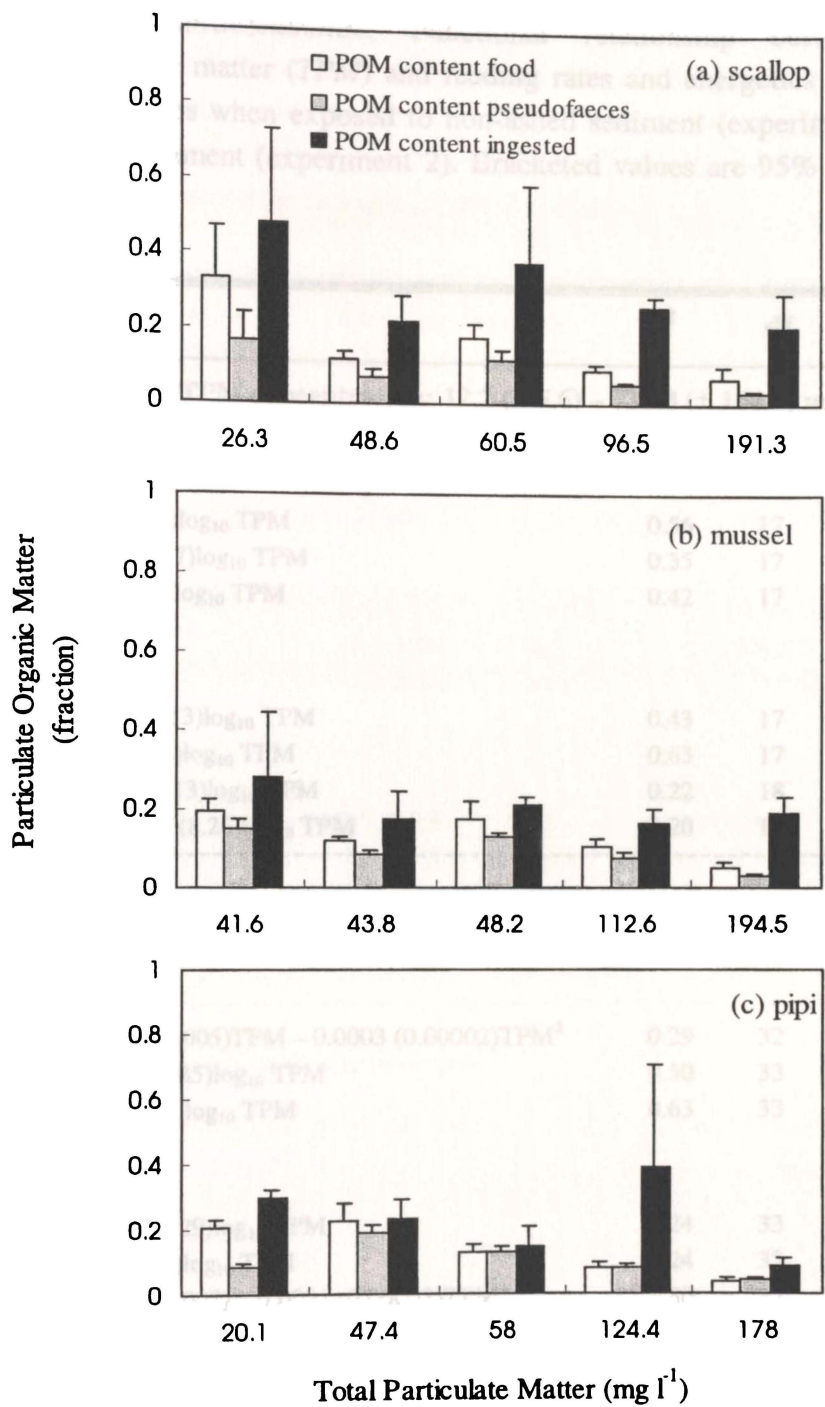


Figure 2.5 Comparison of organic fraction in the diet, pseudofaeces, and ingested matter (± 1 SD) of scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) exposed to ashed sediments added to natural seston during experiment 1. Data are the mean of 12 replicates for diets and 7 replicates for pseudofaeces and ingested organic fraction.

Table 2.5 *Pecten novaezelandiae*. Functional relationship between total particulate matter (TPM) and feeding rates and energetics established for scallops when exposed to non-ashed sediment (experiment 1) and ashed sediment (experiment 2). Bracketed values are 95% confidence intervals

Function	r^2	df	P
Experiment 1 (Range of TPM concentration: 12.2 (\pm 5.6) – 733.3 (\pm 164.7) mg l⁻¹)			
<u>Feeding rates</u>			
CR = 0.66 (0.25) - 0.24 (0.11)log ₁₀ TPM	0.56	17	0.000
RR = 36.70 (18.4) – 11.00 (7.7)log ₁₀ TPM	0.35	17	0.008
IR = 5.52 (3.05) – 2.10 (1.27)log ₁₀ TPM	0.42	17	0.003
<u>Energetics</u>			
OAR = 2.20 (1.22) – 0.87 (0.13)log ₁₀ TPM	0.43	17	0.002
AE = 0.72 (0.15) – 0.27 (0.13)log ₁₀ TPM	0.63	17	0.002
Resp. = 0.42 (0.27) – 0.14 (0.13)log ₁₀ TPM	0.22	18	0.039
SFG = 74.80 (33.51) – 12.44 (8.26)log ₁₀ TPM	0.20	18	0.048
Experiment 2 (Range of TPM concentration: 26.3 (\pm 24.7) – 191.3 (\pm 13.0) mg l⁻¹)			
<u>Feeding rates</u>			
CR = -0.041 (0.22) – 0.008 (0.005)TPM – 0.0003 (0.00002)TPM ²	0.29	32	0.004
RR = -102 (46.07) + 69.5 (24.85)log ₁₀ TPM	0.50	33	0.000
IR = -15.8 (6.04) + 12.0 (3.26)log ₁₀ TPM	0.63	33	0.000
<u>Energetics</u>			
OAR = -2.68 (2.39) + 2.06 (1.29)log ₁₀ TPM	0.24	33	0.003
AE = 1.43 (1.05) – 0.44 (0.10)log ₁₀ TPM	0.24	32	0.003
Resp. = -0.56 (0.32) + 0.03 (0.007) – 0.0001 (0.00003)TPM ²	0.80	17	0.000
SFG	ns		

Note: ns denotes non significant relationship with TPM

Table 2.6 *Pecten novaezelandiae*. Summary of compensation index (*CI*) values for organic fraction and total pigment, when scallops were exposed to different total particulate matter (*TPM*) concentrations composed of different particulate organic matter (*POM*) fractions during experiment 1 (non-ashed sediment) and 2 (ashed sediment)

TPM Diet (mg l⁻¹)	POM fraction Diet (fraction)	Organic fraction CI	t-test	Total pigment CI	t-test
<u>Experiment 1.</u>					
12.4 ± 5.6	0.29 ± 0.13	-	-	-	-
39.3 ± 8.9	0.17 ± 0.04	-	-	-	-
82.2 ± 10.5	0.14 ± 0.02	5.4 ± 1.1	P<0.05	19.9 ± 13.9	ns
205.3 ± 27.6	0.10 ± 0.01	-1.0 ± 0.0	ns	-2.9 ± 3.5	ns
733.3 ± 164.7	0.10 ± 0.01	-1.0 ± 0.0	ns	-1.0 ± 0.0	ns
<u>Experiment 2.</u>					
26.3 ± 24.7	0.33 ± 0.14	0.7 ± 0.9	ns	-8.6 ± 7.3	ns
60.5 ± 55.8	0.17 ± 0.04	1.0 ± 1.2	ns	-29.9 ± 21.1	ns
48.6 ± 11.4	0.12 ± 0.02	0.8 ± 0.6	p<0.05	-7.4 ± 8.7	ns
96.5 ± 11.08	0.09 ± 0.02	1.1 ± 0.3	p<0.05	-27.2 ± 11.6	ns
191.3 ± 13.0	0.07 ± 0.04	2.9 ± 2.2	p<0.05	-51.1 ± 53.0	ns

Note: ns denotes not significantly different from zero

2.5.2.2 Scallop (*Pecten novaezelandiae*) Energetics

Organic absorption rates (*OAR*) for *Pecten novaezelandiae*, during experiment 1, decreased from a maximum of $1.54 (\pm 1.36) \text{ mg h}^{-1} \text{ g}^{-1}$ to minimal values of $<0 \text{ mg h}^{-1} \text{ g}^{-1}$ when *TPM* increased to $205.3 (\pm 27.6) \text{ mg l}^{-1}$ (Fig. 2.6a) as best described by a logarithmic equation (Table 2.4). In experiment 2, *OAR* increased at a decreasing rates with increased in *TPM* concentrations (Fig.2.6a), despite the fact that *POM* fraction had been diluted by the addition of ashed sediment (Table 2.1). The relationship was best described by a logarithmic function (Table 2.4).

For both diets, absorption efficiency (*AE*) decreased as *TPM* concentrations increased (Fig. 2.7a) in a relationship best described by logarithmic functions (Table 2.5).

The relationships between respiration rate and *TPM* were best expressed by a logarithmic function in experiment 1, and a polynomial function in experiment 2 (Table 2.5). Respiration rate reduced significantly with increasing *TPM* concentrations during experiment 1. A polynomial relation in experiment 2 revealed that *Pecten novaezelandiae* displayed a maximum value of respiration rate when *TPM* concentration was $96.5 (\pm 11.08) \text{ mg l}^{-1}$ before decreasing (Fig 2.6b).

As a consequence of different patterns observed for energy gain through organic absorption and expenditure via respiration over a wide range of *TPM* concentrations, different patterns in scope for growth (*SFG*) were revealed (Fig 2.6c). In experiment 1, *SFG* decreased from maximum value recorded at $82.2 (\pm 10.6) \text{ mg l}^{-1}$ to zero when *TPM* reached 407.6 mg l^{-1} according to a logarithmic function (Table 2.5). In experiment 2, *SFG* was not significantly affected by *TPM* concentrations. Nevertheless, the values were still very low.

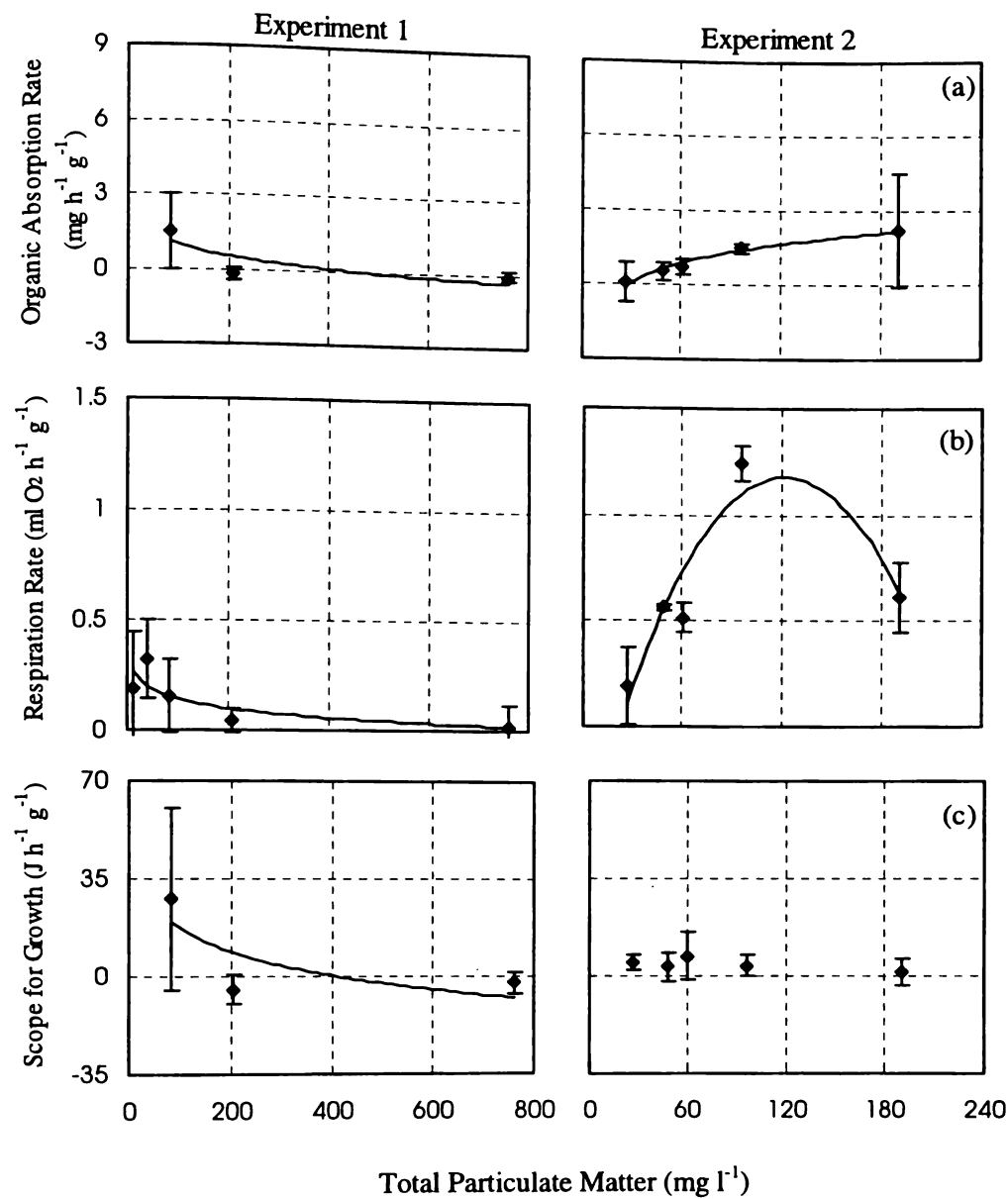


Figure 2.6 *Pecten novaezelandiae*. (a) Organic absorption rate (OAR), (b) respiration rate (Resp.) and (c) scope for growth (SFG) standardised to 1 g dry tissue weight for scallops, exposed to different concentrations of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data are the mean of 7 replicates for OAR, and mean of 4 replicates for Resp. and SFG (\pm 1SD)

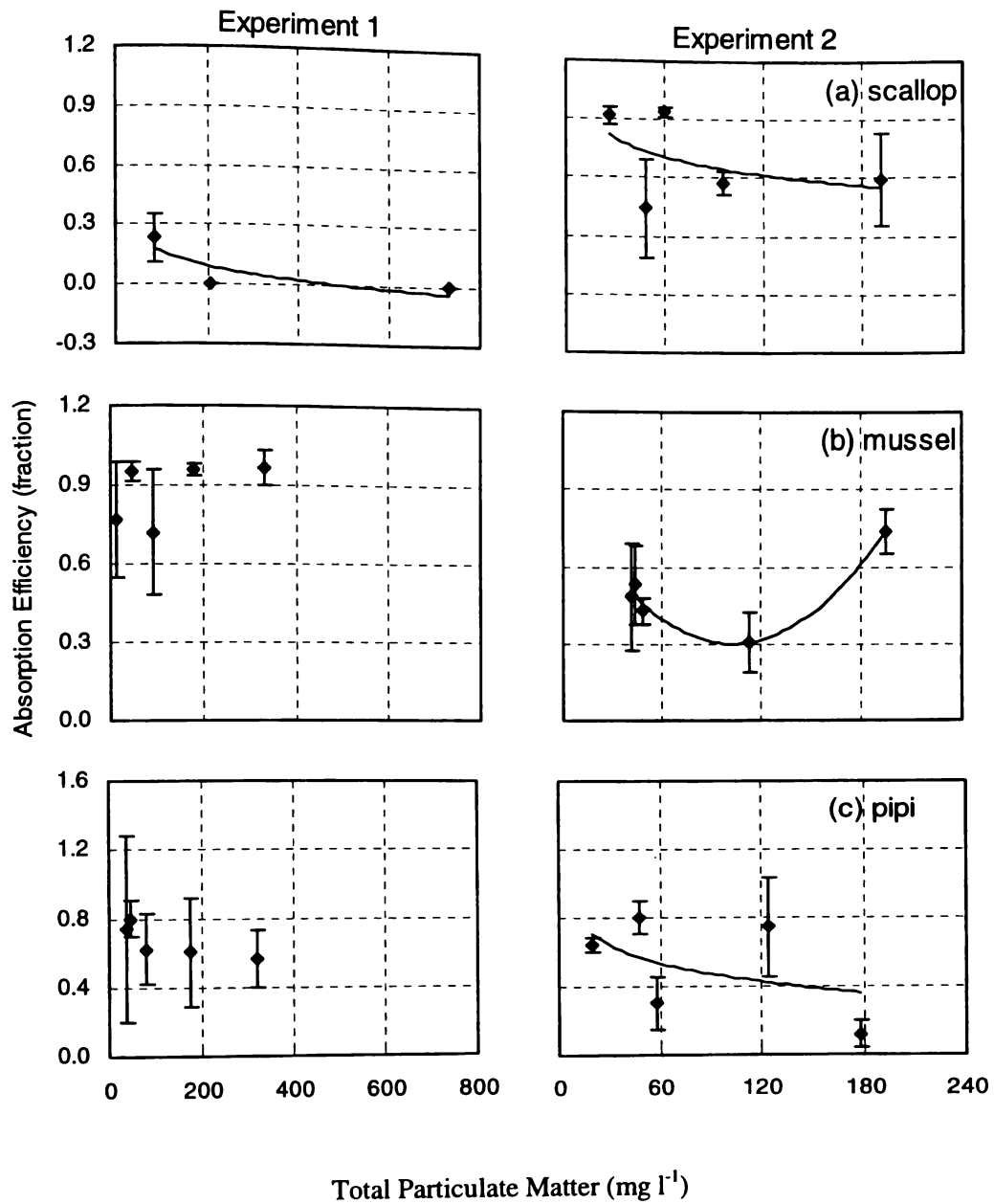


Figure 2.7 Absorption efficiency (± 1 SD) standardised to 1 g dry tissue weight for (a) scallops (*Pecten novaezelandiae*) (b) mussels (*Perna canaliculus*) and (c) pipis (*Paphies australis*), as a function of total particulate matter in experiment 1 (non-ashed sediment), and experiment 2 (ashed sediment)

2.5.2.3 Feeding Rates of Mussel (*Perna canaliculus*)

In experiment 1 *CR* was negatively correlated with *TPM* (Fig. 2.8a) and was best described by a logarithmic function, while in experiment 2 the relationship between *CR* and *TPM* was best described by a polynomial function (Table 2.7). The polynomial relationship revealed two maxima in *CR* values at the extremes of *TPM* concentrations. The lowest *CR* value was recorded when *TPM* concentration was at $112.6 (\pm 22.7) \text{ mg l}^{-1}$ (Fig 2.8a).

The relationship between rejection rates (*RR*) and *TPM* differed between experiments. When non-ashed sediment was used in experiment 1, *RR* increased at a low rate with increasing *TPM* concentrations, but slightly decreased when the *TPM* concentrations increased beyond $176 (\pm 13.4) \text{ mg l}^{-1}$ (Fig 2.8b). This relationship was best described by a polynomial equation (Table 2.7). On the contrary, the use of ashed sediments in experiment 2 produced an exponential relationship between the variables (Fig. 2.8b and Table 2.7). Mussels feeding on ashed sediments produced relatively more pseudofaeces than mussels feeding on non-ashed sediments (Fig. 2.8b).

Considering the decrease in *CR* and low *RR* in experiment 1, the estimated ingestion rates (*IR*) was consistently low as *TPM* concentrations increased (Fig. 2.8c). At the lowest *TPM* concentrations ($13.0 \pm 7.0 \text{ mg l}^{-1}$) *IR* was $3.12 \pm 3.90 \text{ mg h}^{-1} \text{ g}^{-1}$ whereas at $331.5 (\pm 32.1) \text{ mg l}^{-1}$ *IR* was $2.06 \pm 3.90 \text{ mg h}^{-1} \text{ g}^{-1}$ (Fig 2.8c). Inversely, in experiment 2, *IR* increased from $10.56 (\pm 5.18)$ to $26.73 (\pm 5.87) \text{ mg h}^{-1} \text{ g}^{-1}$ when *TPM* concentrations increased from $41.6 (\pm 16.3) \text{ mg l}^{-1}$ to $194.5 (\pm 24.7) \text{ mg l}^{-1}$.

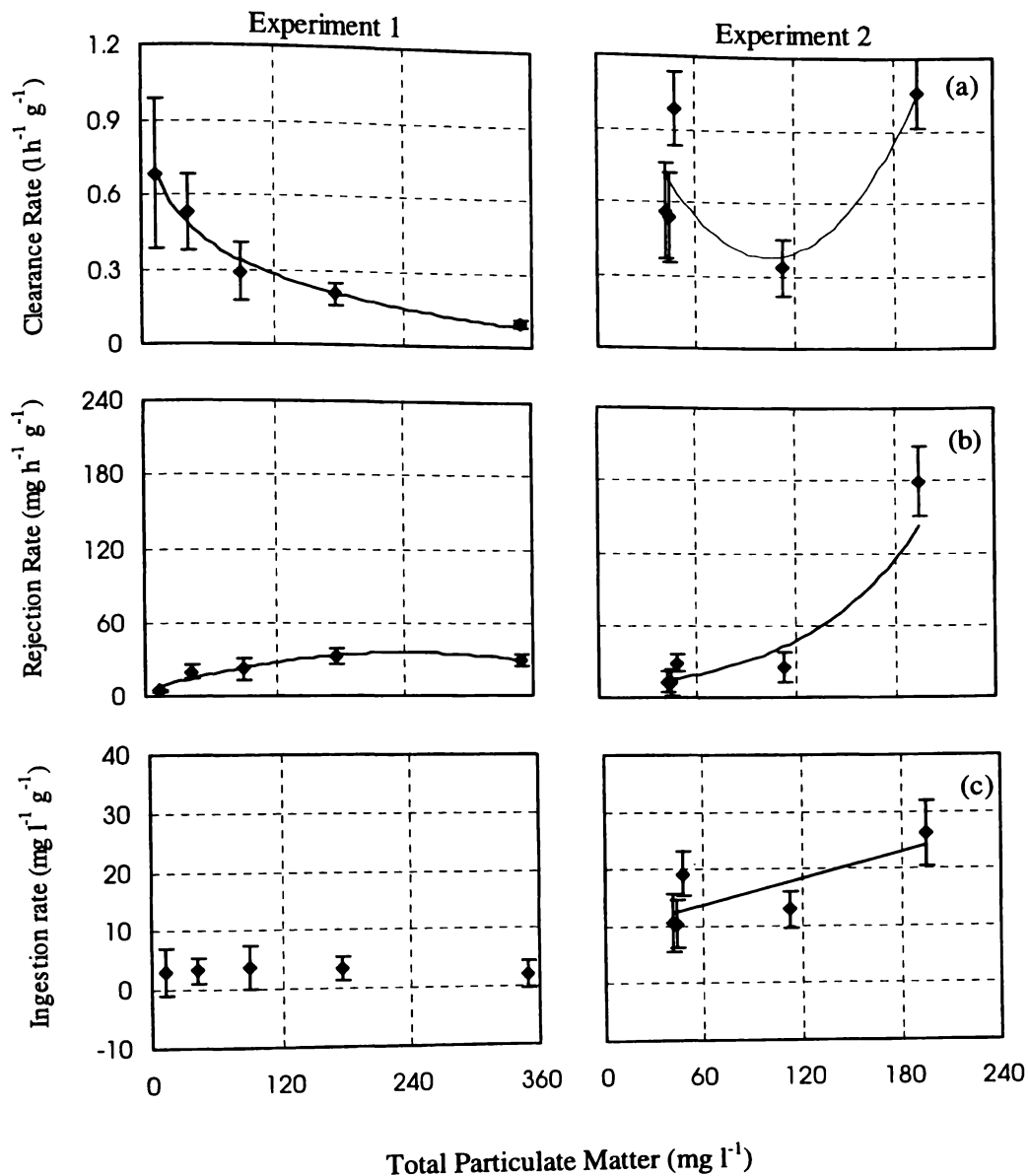


Figure 2.8 *Perna canaliculus*. (a) Clearance (b) rejection and (c) ingestion rates standardised to 1 g dry tissue weight for mussels, exposed to different concentration of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data represent the mean of 7 replicates (± 1 SD)

Table 2.7 *Perna canaliculus*. Functional relationship between total particulate matter (TPM) and feeding rates and energetics established for mussels when exposed to non-ashed sediment (experiment 1) and ashed sediment (experiment 2). Bracketed values are 95% confidence intervals

Function	r^2	df	p
Experiment 1 (Range of TPM concentration: 13.0 (\pm 7.0) – 331.5 (\pm 32.1) mg l⁻¹)			
<u>Feeding rates</u>			
CR = 1.20 (0.23) - 0.44 (0.12)log ₁₀ TPM	0.69	27	0.000
RR = 4.65 (1.01) + 0.25 (0.09)TPM + 0.0005 (0.00001)TPM ²	0.35	26	0.000
IR	ns		
<u>Energetics</u>			
OAR	ns		
AE	ns		
Resp. = -0.03(0.12) + 0.003(0.002)TPM + 0.000009(0.000006)TPM ²	0.39	17	0.014
SFG	ns		
Experiment 2 (Range of TPM concentration: 41.6 (\pm 16.3) – 194.5 (\pm 24.7) mg l⁻¹)			
<u>Feeding rates</u>			
CR = 1.30 (0.42) – 0.02 (0.01)TPM + 0.0008 (0.00004)TPM ²	0.41	32	0.000
RR = 7.81 (3.21) ^{0.0149 (0.001) TPM}	0.59	33	0.000
IR = 8.89 (3.64) + 0.08 (0.03)TPM	0.40	33	0.000
<u>Energetics</u>			
OAR = 2.31 (1.63) - 0.041 (0.02)TPM – 0.002 (0.0005)TPM ²	0.47	32	0.003
AE = 0.82 (0.21) + 0.01 (0.005)TPM – 0.00005 (0.00002)TPM ²	0.50	32	0.003
Resp. = 2.31 (1.54) - 0.042 (0.02)TPM – 0.002 (0.0005)TPM ²	0.53	17	0.000
SFG = 38.4 (24.73) – 17.2 (13.19)log ₁₀ TPM	0.30	18	0.013

Note: ns denotes non significant relationship with TPM

Mussels have the capability to alter the amount of ingested matter by rejecting proportionately less organic particles in pseudofaeces relative to that in diet (Fig 2.4b and 2.5b). Furthermore, the compensation index (*CI*) (Table 2.8) indicated that mussels produced sufficient pseudofaeces to significantly increased the ingested organic fraction when particulate organic matter (*POM*, fraction) was diluted to $\leq 0.15 \pm 0.04$ and to $\leq 0.16 \pm 0.04$ in experiment 2 and 1 respectively. Similar to scallops, mussels were unable to increase the quality of total pigment before ingestion as indicated by non-significant *CI*.

2.5.2.4 Mussel (*Perna canaliculus*) Energetics

The organic absorption rate (*OAR*) of *Perna canaliculus* was not significantly affected by *TPM* in experiment 1 (Fig 2.9a), whereas in experiment 2, the relationship between *OAR* and *TPM* concentration (Fig 2.9a) was best described by a polynomial function (Table 2.7). The function indicated that *OAR* decrease slightly at lower *TPM* concentrations before increasing as *TPM* concentration increased further.

Similarly, *AE* was also not affected by increasing *TPM* concentrations when non-ashed sediments were utilised (experiment 1). When ashed sediment was utilised (experiment 2), the relationship was best described by a polynomial function (Fig 2.7b, Table 2.7). The function revealed that *AE* decreased slightly when *TPM* concentration increased from $\approx 50 \text{ mg l}^{-1}$ to $< 120 \text{ mg l}^{-1}$ but increased as *TPM* concentrations increased further.

Figure 2.9b illustrates the relationship between respiration rates and *TPM* concentrations. In both experiments, the relationships were best described by

Table 2.8 *Perna canaliculus*. Summary of compensation index (CI) values for organic fraction and total pigment, when mussels were exposed to increasing total particulate matter (TPM) concentrations composed of different particulate organic matter (POM) fractions during experiment 1 (non-ashed sediment) and 2 (ashed sediment).

TPM Diet (mg l ⁻¹)	POM Diet (fraction)	Organic fraction CI	t-test	Total pigment CI	t-test
<u>Experiment 1.</u>					
13.0 ± 7.0	0.28 ± 0.09	0.7 ± 0.8	ns	-0.1 ± 0.5	ns
43.9 ± 10.6	0.16 ± 0.04	3.2 ± 0.4	P<0.05	-1.1 ± 2.9	ns
90.1 ± 13.2	0.12 ± 0.01	2.7 ± 2.6	ns	-2.0 ± 2.4	ns
176.4 ± 13.4	0.11 ± 0.01	7.0 ± 1.5	P<0.05	-10.3 ± 9.2	P<0.05
331.5 ± 32.1	0.10 ± 0.02	5.2 ± 0.7	P<0.05	-11.8 ± 8.8	P<0.05
<u>Experiment 2.</u>					
48.2 ± 23.2	0.15 ± 0.04	0.2 ± 0.1	P<0.05	-1.7 ± 1.6	ns
41.6 ± 16.3	0.19 ± 0.03	0.5 ± 0.9	ns	*-37.9 ± 80.9	ns
43.8 ± 7.8	0.12 ± 0.02	0.5 ± 0.6	p<0.05	-5.0 ± 5.6	ns
112.6 ± 22.7	0.11 ± 0.02	0.6 ± 0.3	p<0.05	-18.7 ± 10.5	ns
194.5 ± 24.7	0.05 ± 0.01	2.8 ± 0.8	p<0.05	-17.7 ± 11.5	ns

Note: ns denotes not significantly different from zero

* Wilcoxon rank test

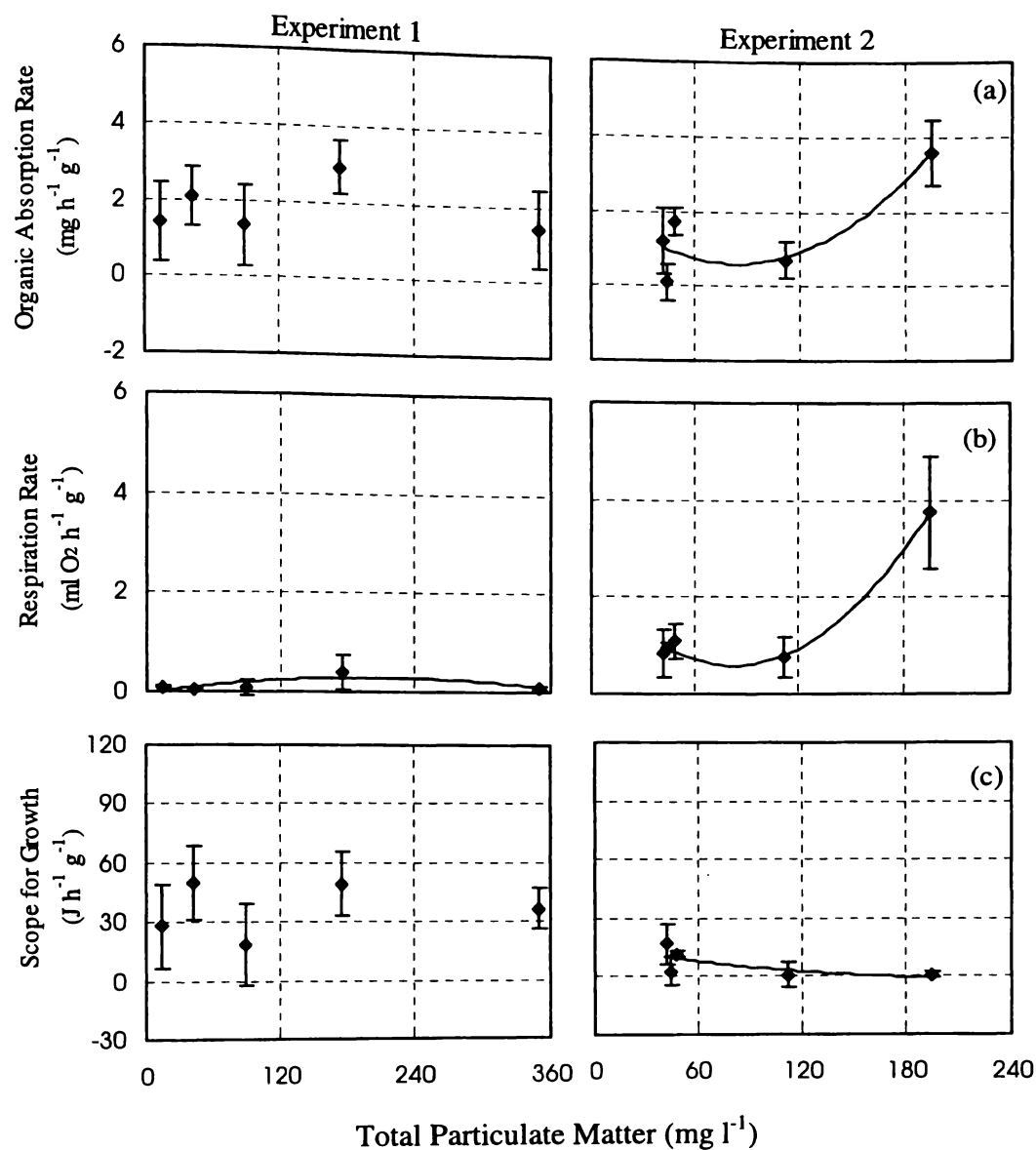


Figure 2.9 *Perna canaliculus*. (a) Organic absorption rate (OAR), (b) respiration rate (Resp.) and (c) scope for growth (SFG) standardised to 1 g dry tissue weight for scallops, exposed to different concentrations of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data are the mean of 7 replicates for OAR, and mean of 4 replicates for Resp. and SFG (\pm 1SD)

polynomial functions (Table 2.7). However, respiration rates observed in experiment 1 were comparatively lower to respiration rates observed in experiment 2. In experiment 2, the polynomial curve revealed that a slight decrease in respiration rates at lower *TPM* concentrations preceded a high increased respiration rate when *TPM* concentration increased beyond 120 mg l⁻¹.

Scope for growth (*SFG*) was positive when the diet mixture was composed of non-ashed sediments in experiment 1, and it was not affected by *TPM* concentrations (Fig. 2.9c). *SFG* decreased to 0.54 (± 1.35) Jh⁻¹ g⁻¹ at 194.5 (± 24.7) mg l⁻¹ *TPM* concentration during experiment 2 when ashed sediments were used in the diet mixture. The relationship was best described by a logarithmic function (Table 2.7).

2.5.2.5 Feeding Rates of Pipi (*Paphies australis*)

Clearance rate (*CR*) was low and not affected by *TPM* concentrations when non ashed sediment was used in the diet mixtures in experiment 1 (Fig 2.10a). Whereas the relationship between the two variables in experiment 2 was best described by a polynomial function (Table 2.9 and Fig. 2.10a). *CR* decreased dramatically from a maximum of 0.77 (± 0.25) lh⁻¹ g⁻¹ recorded at 20.1 (± 3.6) mg l⁻¹ to a minimum value at 47.4 (± 35.1) mg l⁻¹ *TPM* concentration. Following that a slight increase with *TPM* concentration was observed.

Rejection rate (*RR*) for both experiments were best described by linear equations (Fig 2.10b, Table 2.9). However, *P. australis* only have the capacity to modify the organic content of the ingested material by rejecting proportionately less organic particles in pseudofaeces at the lowest *TPM* concentrations in both experiments, 39.0 (± 23.8) mg l⁻¹ in experiment 1 and 20.1 (± 3.6) mg l⁻¹ (Fig 2.3c and

2.4c). Beyond these *TPM* concentrations *CI* was not significantly different from zero. Similarly, *CI* values for total pigment were not significantly different from zero (Table 2.10).

The estimated ingestion rate (*IR*) for *P. australis* in experiment 1 was consistently low but stable as *TPM* concentrations increased. *IR* was $1.74 (\pm 2.58) \text{ mg h}^{-1} \text{ g}^{-1}$ and $0.88 (\pm 1.30) \text{ mg h}^{-1} \text{ g}^{-1}$ at the lowest and highest *TPM* concentrations respectively (Fig 2.10c). In experiment 2, *IR* initially decreased from $8.72 (\pm 3.33) \text{ mg h}^{-1} \text{ g}^{-1}$ to $0.60 (\pm 1.30) \text{ mg h}^{-1} \text{ g}^{-1}$ as *TPM* concentration increased from $20.1 (\pm 3.6) \text{ mg l}^{-1}$ to $47.4 (\pm 35.1) \text{ mg l}^{-1}$. However, as *TPM* increased to $178.0 (\pm 11.5) \text{ mg l}^{-1}$ *IR* also increased to $10.92 (\pm 3.24) \text{ mg h}^{-1} \text{ g}^{-1}$.

2.5.2.6 Pipi (*Paphies australis*) Energetics

The relationship between organic absorption rate (*OAR*) and *TPM* concentration in experiment 1 could not be explained sufficiently by either linear, polynomial, logarithmic or exponential functions (Fig 2.11a). However, *OAR* attained zero values when *TPM* concentrations at $176.7 (\pm 17.0) \text{ mg l}^{-1}$. In experiment 2, a logarithmic equation (Table 2.9) best described the relationship between the two variables. Still, *OAR* decreased dramatically as *TPM* concentrations increased beyond $20.1 (\pm 3.6) \text{ mg l}^{-1}$. Similarly, the efficiency at which these organic fractions are absorbed (*AE*) was not significantly affected by *TPM* concentrations in experiment 1, whereas in experiment 2, a logarithmic function (Table 2.6) best described the relationship (Fig 2.7c).

Energy expenditure as depicted by curves for respiration rates (Fig 2.11b) showed that in experiment 1, respiration rate reached a maximum of $>0.4 \text{ ml O}_2 \text{ h}^{-1} \text{ g}^{-1}$

within the range of 200-220 mg l⁻¹ *TPM* before decreasing with further increases in *TPM* concentration. In contrast, respiration rates in experiment 2 were not significantly affected by *TPM* concentration.

Fig 2.11c illustrates that *SFG* were high at the lowest *TPM* concentrations (Table 2.3), but decreased to near zero as *TPM* concentration increases further. The relationships were best described by logarithmic functions (Table 2.9).

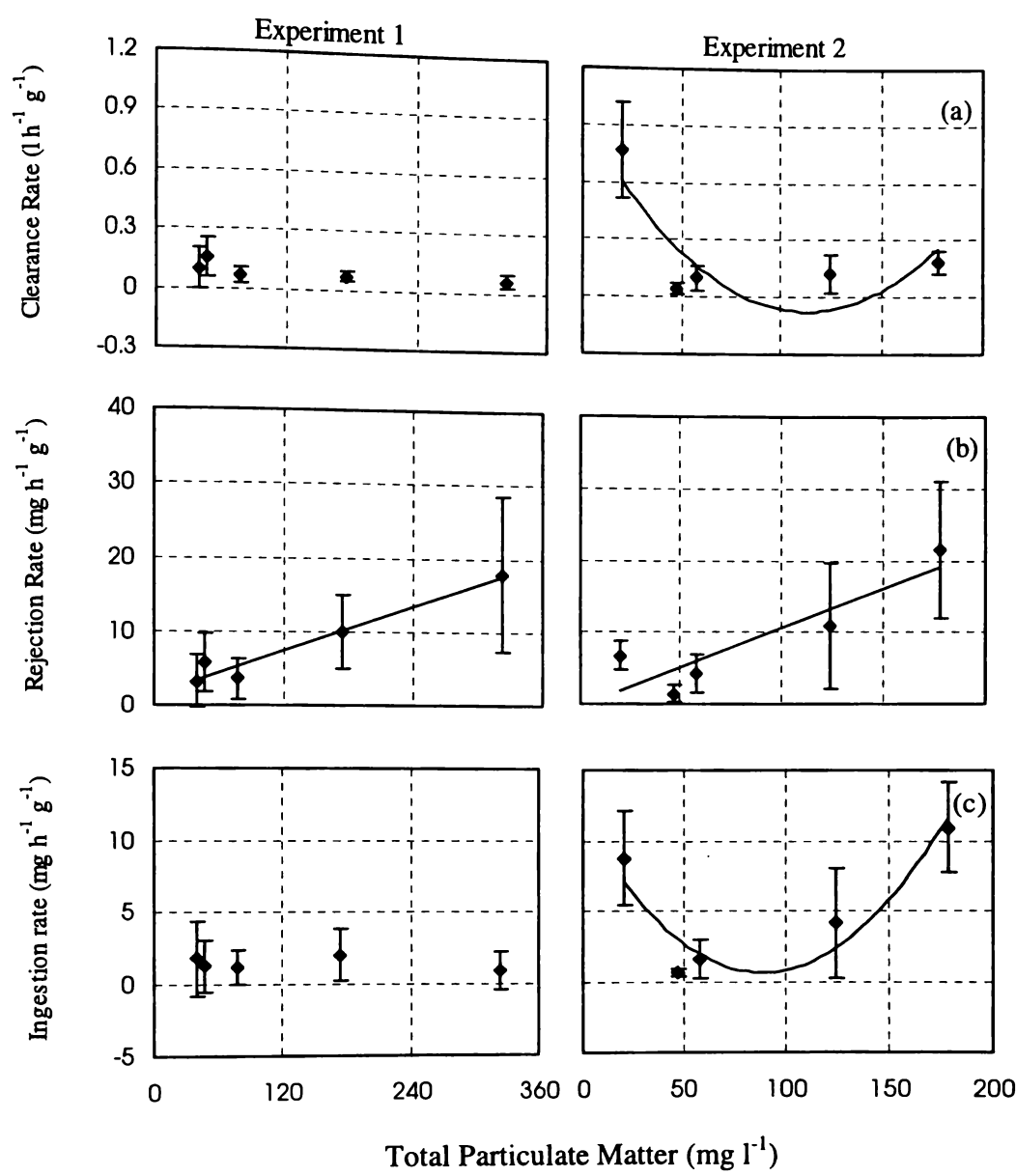


Figure 2.10 *Paphies australis*. (a) Clearance (b) rejection and (c) ingestion rates standardised to 1 g dry tissue weight for pipis, exposed to different concentration of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data represent the mean of 7 replicates (± 1 SD)

Table 2.9 *Paphies australis*. Functional relationship between total particulate matter (TPM) and feeding rates and energetics established for pipis when exposed to non-ashed sediment (experiment 1) and ashed sediment (experiment 2). Bracketed values are 95% confidence intervals

Function	r^2	df	P
Experiment 1 (Range of TPM concentration: 39.0 (\pm 23.8) – 322.2 (\pm 19.6) mg l⁻¹)			
<u>Feeding rates</u>			
CR	ns		
RR = 1.52 (3.47) + 0.05 (0.02)TPM	0.45	28	0.000
IR	ns		
<u>Energetics</u>			
OAR	ns		
AE	ns		
Resp. = -0.284 (0.22) + 0.008 (0.006)TPM – 0.00002 (0.000009)TPM ²	0.76	17	0.000
SFG = 26.9 (22.98) – 13.0 (11.43)log ₁₀ TPM	0.24	18	0.028
Experiment 2 (Range of TPM concentration: 20.1 (\pm 3.6) – 178.0 (\pm 11.5) mg l⁻¹)			
<u>Feeding rates</u>			
CR = 0.93 (0.23) – 0.018 (0.006) TPM + 0.0001 (0.00003) TPM ²	0.55	32	0.000
RR = -0.42 (4.06) + 0.11 (0.04)TPM	0.49	33	0.000
IR = 11.5 (3.6) – 0.25 (0.09)TPM + 0.001 (0.0005)TPM ²	0.60	32	0.000
<u>Energetics</u>			
OAR = 2.26 (1.03) - 1.16 (0.26)log ₁₀ TPM	0.36	32	0.000
AE = 1.44 (0.49) – 0.52 (0.10)log ₁₀ TPM	0.33	32	0.000
Resp.	ns		
SFG = 68.8 (28.51) – 32.7 (15.43) log ₁₀ TPM	0.52	18	0.000

Note: ns denotes non significant relationship with TPM

Table 2.10 *Paphies australis*. Summary of compensation index (CI) values for organic fraction and total pigment, when pipi was exposed to increasing total particulate matter (TPM) concentrations composed of different particulate organic matter (POM) fractions during experiment 1 (non-ashed sediment) and 2 (ashed sediment)

TPM Diet (mg l ⁻¹)	POM Diet (fraction)	Organic fraction CI	t-test	Total pigment CI	t-test
<u>Experiment 1.</u>					
39.0 ± 23.8	0.26 ± 0.20	1.1 ± 0.6	P<0.05	-0.6 ± 1.0	ns
46.8 ± 15.0	0.15 ± 0.02	1.0 ± 1.4	ns	0.3 ± 2.9	ns
77.1 ± 11.4	0.15 ± 0.02	1.2 ± 1.5	ns	0.1 ± 0.0	ns
176.7 ± 17.0	0.12 ± 0.04	-0.5 ± 0.3	ns	-0.2 ± 2.5	P<0.05
322.2 ± 19.6	0.10 ± 0.04	0.8 ± 0.5	ns	-30.6 ± 37.4	P<0.05
<u>Experiment 2.</u>					
47.4 ± 35.1	0.22 ± 0.05	0.03 ± 0.3	ns	-52.0 ± 0.0	P<0.05
20.1 ± 3.6	0.20 ± 0.03	0.5 ± 0.1	P<0.05	-8.3 ± 5.3	ns
58.0 ± 32.1	0.13 ± 0.02	*0.1 ± 0.5	ns	-101.4 ± 117	ns
124.4 ± 58.7	0.07 ± 0.02	4.1 ± 4.1	ns	-153.1 ± 120	ns
178.0 ± 11.5	0.03 ± 0.01	1.2 ± 0.6	ns	-43.6 ± 25.5	ns

Note: ns denotes not significantly different from zero

* Wilcoxon rank test

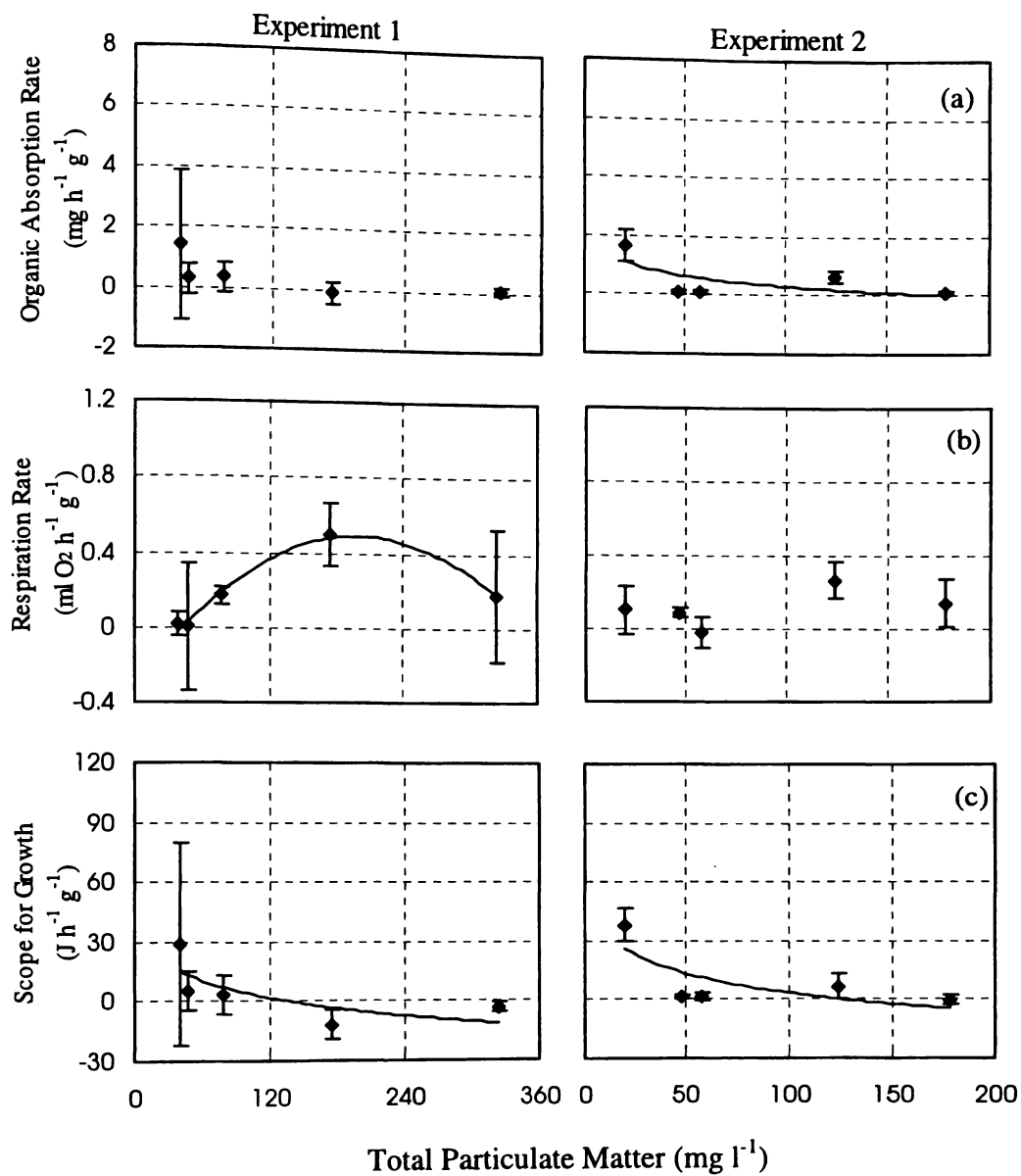


Figure 2.11 *Paphies australis*. (a) Organic absorption rate (*OAR*), (b) respiration rate (*Resp.*) and (c) scope for growth (*SFG*) standardised to 1 g dry tissue weight for pipis, exposed to different concentrations of total particulate matter in experiment 1 (non-ashed sediment) and experiment 2 (ashed sediment). Data are the mean of 7 replicates for *OAR*, and mean of 4 replicates for *Resp.* and *SFG* (\pm 1SD)

2.6.3 Feeding rates and Energetics of Bivalves Exposed to 20 mg l⁻¹ TPM Concentrations Added to Natural Seston

2.6.3.1 Scallops (*Pecten novaezelandiae*)

TPM concentrations were similar between the non-ashed and ashed sediments (Table 2.11 and 2.12), but, *POM* fraction were significantly different ($p < 0.001$) between the two sediment treatments. *POM* was higher when non-ashed sediment was used in the diet mixture than ashed sediment.

CR and *RR* were similar between the two diets despite the differences in the *POM* fraction (Fig. 2.12 and Table 2.13). In addition, the scallop was able to significantly alter the organic content of ingested matter (Table 2.14) when exposed to these *TPM* concentrations. Furthermore, the sediment quality had no significant effect on *OAR* and *AE* (Table 2.13). However, organic content had a significant ($p < 0.05$) effect on respiration rate. High respiration rates were reported when the diet was composed of ashed sediment (Fig. 2.12). Despite these differences *SFG* did not differ between diets

2.6.3.2 Mussels (*Perna canaliculus*)

As a consequence of a substantial fluctuations in the natural seston concentration (Table 2.11), the diet *TPM* concentrations used in both diet mixture were significantly different ($p < 0.05$) (Table 2.12). High *TPM* concentrations were recorded in the diet mixture containing ashed sediment. Similarly, *POM* concentrations were significantly

different between the two diets mixture. A diet made up of the ashed sediment had lower *POM* concentrations than a diet composed of non-ashed sediment.

CR was significantly different between the diet qualities ($p < 0.05$) (Table 2.13). A diet composed of ashed sediment which had higher *TPM* concentrations had significantly lower *CR* (Fig 2.12). Inversely, the use of non-ashed sediment in the diet mixture which had lower *TPM* concentration had significantly higher *CR*. Despite the differences in *TPM* concentration and *POM* fraction, the amount of sediments rejected as pseudofaeces (*RR*) were not significantly different between the two diet mixtures. In addition, at these *TPM* concentrations, the mussel can still increased the ingested organic fraction as depicted by significant *CI* (Table 2.14).

The use of ashed and non-ashed sediments in the diet mixtures had no significant effect on *OAR*, *AE*, respiration rate, or on *SFG* (Fig 2.12 and Table 2.13), eventhough the two diet mixtures contained different *TPM* concentrations and *POM* fractions.

2.6.3.3 Pipis (*Paphies australis*)

Similar to the mussel diets, *TPM* concentrations were significantly different ($p < 0.05$) between ashed and non-ashed diets (Table 2.11 and 2.12). A diet composed of ashed sediment had significantly higher *TPM* concentration than the non-ashed diet mixture (Fig 2.12). Similarly, *POM* fraction were significantly different between the diets. Low *POM* fraction was reported when ashed sediments were used in the diet mixture and vice versa for non-ashed sediment.

Similar to mussels, *CR* for pipis were significantly different between the diet qualities ($p < 0.05$) (Table 2.13). A diet composed of ashed sediment which had higher

TPM concentrations had significantly lower *CR* (Fig 2.12). On the contrary, the use of non-ashed sediment in the diet mixture which had lower *TPM* concentration had significantly higher *CR*. Despite that, the diet mixtures containing different *TPM* concentrations and *POM* fractions had no significant effect on *RR*. *Pipis* were unable to significantly alter the ingested organic fraction at these *TPM* concentrations (Table 2.14).

OAR, *AE*, respiration rates and *SFG* were significantly different ($p < 0.05$) between the diet mixtures (Table 2.13). Higher rates were recorded for diet composed of non-ashed sediment than a diet composed of ashed sediment (Fig 2.12).

Table 2.11 Mean concentrations of total particulate matter (*TPM*) , total pigment, and particulate organic matter (*POM*) fraction in the diet mixtures composed of 20 mg l⁻¹ of either ashed or non-ashed sediments during experiment 2 (September 1998). Mean concentrations of natural *TPM*, and proportion of *POM* used in the dietary mixture are also shown

Component Source	TPM diet (mg l ⁻¹)	TPM natural (mg l ⁻¹)	POM diet (fraction)	POM natural (fraction)	Total pigment diet (µg mg ⁻¹)
SCALLOP (<i>Pecten novaezelandiae</i>)					
1. Natural seston + **20 mg l ⁻¹ (mean ± sd)	48.6 ± 11.4	28.6 ± 11.4	0.12 ± 0.02	0.21 ± 0.04	52.6 ± 20.4
2 Natural seston + *20 mg l ⁻¹ (mean ± sd)	49.2 ± 12.74	29.17 ± 12.7	0.16 ± 0.02	0.23 ± 0.06	43.1 ± 10.1
MUSSEL (<i>Perna canaliculus</i>)					
1. Natural seston + **20 mg l ⁻¹ (mean ± sd)	43.8 ± 7.5	23.8 ± 7.5	0.12 ± 0.02	0.22 ± 0.04	29.2 ± 11.1
2. Natural seston + *20 mg l ⁻¹ (mean ± sd)	33.4 ± 2.9	13.4 ± 2.9	0.14 ± 0.01	0.27 ± 0.03	57.6 ± 23.5
PIPI (<i>Paphies australis</i>)					
1. Natural seston + **20 mg l ⁻¹ (mean ± sd)	58.0 ± 32.1	38.0 ± 32.1	0.13 ± 0.02	0.24 ± 0.08	28.2 ± 9.0
2 Natural seston + *20 mg l ⁻¹ (mean ± sd)	33.2 ± 3.8	13.2 ± 3.8	0.18 ± 0.03	0.36 ± 0.10	62.7 ± 17.8

** ashed sediments

* non-ashed sediments

Table 2.12 Summary of p values from a one-way ANOVA comparing total particulate matter (*TPM*) concentration and particulate organic matter (*POM*) fraction within the diets of scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) for the 20 mg l⁻¹ sediments added to natural seston

Species	Diet composition	Source of variation	df	p
Scallop	TPM	Diet	1	0.904
		Error	22	
	POM fraction	Diet	1	0.000
		Error	22	
Mussel	TPM	Diet	1	0.000
		Error	22	
	POM fraction	Diet	1	0.005
		Error	22	
Pipi	TPM	Diet	1	0.014
		Error	22	
	POM fraction	Diet	1	0.001
		Error	22	

Figure 2.12 (a) Clearance rate (*CR*), (b) rejection rate (*RR*), (c) organic absorption rate (*OAR*), (d) absorption efficiency (*AE*), (e) respiration rate (*Resp.*), and (f) scope for growth (*SFG*) for scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) when exposed to 20 mg l⁻¹ diet composed of either ashed or non-ashed sediment mixed with natural seston. Data are the mean of 7 replicates for *CR*, *RR*, *OAR*, *AE*, and 4 replicates for *Resp.* and *SFG* (\pm 1SD)

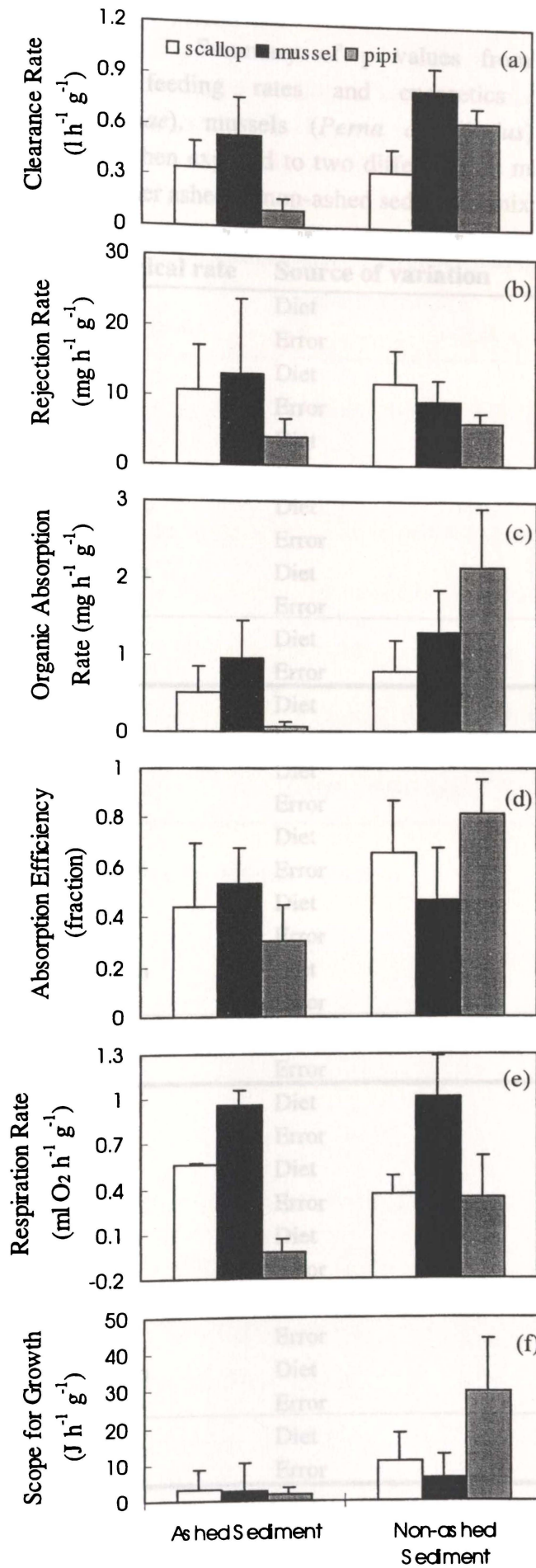


Table 2.13 Summary of p values from analysis of variance comparing feeding rates and energetics for scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*), when exposed to two different diet mixtures composed of 20 mg l⁻¹ of either ashed or non-ashed sediments mixed with natural seston

Species	Physiological rate	Source of variation	df	p
Scallop	CR	Diet	1	0.903
		Error	12	
	RR	Diet	1	0.242
		Error	12	
	OAR	Diet	1	0.199
		Error	12	
	AE	Diet	1	0.105
		Error	12	
	Respiration	Diet	1	0.020
		Error	6	
	SFG	Diet	1	0.145
		Error	6	
Mussel	CR	Diet	1	0.017
		Error	12	
	RR	Diet	1	0.390
		Error	12	
	OAR	Diet	1	0.276
		Error	12	
	AE	Diet	1	0.529
		Error	12	
	Respiration	Diet	1	0.715
		Error	6	
	SFG	Diet	1	0.508
		Error	6	
Pipi	CR	Diet	1	0.000
		Error	12	
	RR	Diet	1	0.100
		Error	12	
	OAR	Diet	1	0.000
		Error	12	
	AE	Diet	1	0.000
		Error	12	
	Respiration	Diet	1	0.048
		Error	6	
	SFG	Diet	1	0.009
		Error	6	

Table 2.14 Summary of compensation index (*CI*) values for organic fraction and total pigment, when scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*) were exposed to 20 mg l⁻¹ of non-ashed sediment (experiment 1) and ashed sediment (experiment 2) added to natural seston

TPM Diet (mg l ⁻¹)	POM Diet (fraction)	Organic fraction <i>CI</i>	t-test	Total pigment <i>CI</i>	t-test
<u>Scallop</u>					
**48.6 ± 11.4	0.12 ± 0.02	0.8 ± 0.6	P<0.05	-29.9 ± 21.1	ns
*49.2 ± 12.74	0.16 ± 0.02	1.5 ± 1.7	P<0.05	-90.8 ± 172.3	ns
<u>Mussel</u>					
**43.8 ± 7.5	0.12 ± 0.02	0.5 ± 0.6	p<0.05	-37.9 ± 80.9	ns
*33.4 ± 2.9	0.14 ± 0.01	0.1 ± 0.1	p<0.05	-17.7 ± 11.5	ns
<u>Pipi</u>					
**58.0 ± 32.1	0.13 ± 0.02	0.1 ± 0.5	ns	-101.4 ± 117	ns
*33.2 ± 3.8	0.18 ± 0.03	-0.002 ± 0.03	ns	-1.2 ± 1.5	ns

Note: ns denotes not significantly different from zero

** ashed sediments

* non-ashed sediments

2.7 Discussion

2.7.1 Feeding Responses to Different Diet Concentrations and Qualities

Like many bivalve species, *Pecten novaezelandiae*, *Perna canaliculus*, and *Paphies australis* possess some compensatory mechanisms to regulate the amount of ingested organic matter, when exposed to varying levels of suspended sediments with different qualities, to maximise energy gain. These mechanisms include regulation of clearance rates and/or pseudofaeces production which ultimately result in selection of organic matter (Hawkins *et al.*, 1990; Willows, 1992; Bayne *et al.*, 1993).

P. novaezelandiae, and *P. canaliculus* responded differently as shown by clearance and pseudofaeces production rates when exposed to increased concentration of particulate matter composed of different qualities. When the diet is composed of high organic fraction, a decrease in clearance rates was observed in both species (Fig. 2.3a and 2.8a). Coupled with low pseudofaeces production, the reduction in clearance rates observed for *P. canaliculus* may be used to stabilise organic intake since the organic absorption rates were similar between the $13 (\pm 7) \text{ mg l}^{-1}$ and $333.5 (\pm 32.1) \text{ mg l}^{-1}$ TPM concentrations. Studies have also shown with increasing concentrations of diets composed of algal mixtures, suspension feeding bivalves generally decrease clearance rates (Foster-Smith, 1975; Winter 1978, Yukihiro *et al.*, 1998). According to Navarro *et al.*, (1992) reduction of clearance rate would contribute to saving energy when such sorting is irrelevant, that is, on high diet quality. In contrast to *P. canaliculus*, the reduction of clearance rates observed for *P. novaezelandiae* at high sediment

concentrations may be related to physical constraint, such as the capacity to produce pseudofaeces (Barille *et al.*, 1997). The hypothesis of physical constraint rather than physiological clearance rate reduction is supported by the fact that *P. novaezelandiae* received relatively no benefit from reducing clearance rate, since the ingested organic fraction and compensation indices were greatly reduced between $82.2 (\pm 10.6) \text{ mg l}^{-1}$ and $205.3 (\pm 27.6) \text{ mg l}^{-1}$ *TPM* concentration. Indeed, it was observed in this study that *P. novaezelandiae* ceased to produce pseudofaeces immediately after being exposed to *TPM* concentration of $205.3 (\pm 27.6) \text{ mg l}^{-1}$, however, shell gaping was still observed, a sign of debility. This is similar to an observation of Dickie (1958, cited by Pilditch (1997)) when *Placopecten magellanicus* was under stress. In comparison, normal feeding activities were observed when *P. novaezelandiae* were exposed to slightly lower *TPM* concentrations ($191.3 \pm 27.6 \text{ mg l}^{-1}$) in experiment 2. Therefore, a slight increase in *TPM* concentration beyond this value may result in great reduction of ingested organic fraction and organic absorption rates.

A positive correlation between clearance rate and fluctuations of natural seston, with low organic fraction, has been described for the cockle *Cerastoderma edulis*, (Iglesias *et al.*, 1992) and mussel *Mytilus edulis*, (Newell and Shumway, 1993; Hawkins *et al.*, 1996). This study demonstrated a similar trend when *P. canaliculus*, in particular, was fed with diets of low quality. However, depending on the feeding behaviour or capability to tolerate high *TPM* concentrations, clearance rates would decrease at some point with further increases in *TPM* concentrations as observed for *P. novaezelandiae*. In similar circumstances, Barille *et al.*, (1997) also observed an increase in clearance rate for *Crassostrea gigas*, before decreasing after reaching 90 mg l^{-1} . This decrease may be also

due to physical constraint if ingested organic fraction decreased as pallial organs are clogged with sediments. Therefore 90 mg l⁻¹ might be considered as an optimum concentration for *C. gigas*. For *P. novaezelandiae* an optimum *TPM* concentration may be higher than the concentrations used during experiment 2, since ingested organic fraction was increasing despite the decreasing clearance rates. However, it is anticipated that further increase in *TPM* concentration would elevate stress conditions resulting in great reduction in *CR* (Bayne and Newell, 1983). Indeed, *CR* reduced dramatically when scallops was exposed to >200 mg l⁻¹ during experiment 1 (Fig 2.3a) in this study.

Because diet was diluted considerably in experiment 2 compared to experiment 1, high pseudofaeces production rates for the *P. novaezelandiae* and *P. canaliculus* were observed. For instance, at 180 mg l⁻¹ *TPM*, the diets organic fraction in experiment 2 for *P. canaliculus* was less by a factor of two compared to organic fractions in experiment 1. Consequently, pseudofaeces production in experiment 2 for *P. canaliculus* increased four times compared to the rates observed in experiment 1. Although a lower pseudofaeces production was observed for *P. novaezelandiae*, similar differences in production rates between the diets were also observed. These observations are different from those observed by Bacon *et al.*, (1998), where pseudofaeces production rates for an epifaunal scallop *Placopecten magellanicus* were similar between low and high diet qualities. The discrepancy may be due in part to the low range of food concentrations used in their experiment. When bivalves species were exposed to natural sestons (Barille *et al.*, 1997; Hawkins *et al.*, 1996, 1998) and to experimental diets representative of natural seston (Iglesias *et al.*, 1992; Navarro *et al.*, 1992; Bayne *et al.*, 1993), consisting of low organic fraction, high rates of clearance and pseudofaeces production were observed. In fact,

these high feeding rates are employed to compensate for low food quality (Hawkins *et al.*, 1996). In support, ingested organic fraction and organic absorption rates in this current study remained high even when low quality diets were used. Similarly, compensation index values were positive when the organic fraction was diluted to some level (Table 2.1, 2.2 and 2.3), implying that selection of organic fraction is one of the main feeding strategies adopted to maximise energy intake when low food qualities are encountered. Nevertheless, it should be noted that both experiments were conducted at different times of the year, therefore the differences observed in the feeding rates may also be related to the environmental factors such as seasonal changes (Brown, 1988).

The feeding strategy shown by an infaunal species *P. australis* is exceptional. It tends to have low clearance rate with one exception (Fig. 2.10a) and produces relatively low amounts of pseudofaeces even at high *TPM* concentrations for both diet qualities. Bacon *et al.*, (1998) showed that an infaunal clam *Mya arenaria* did not rely on the production of pseudofaeces to regulate the amount of ingested organic fraction. This study demonstrated a similar phenomenon. A negative consequence of the low clearance rate, however, is that the chances of increasing the volume of nutritious particles through selection are less as a reduced volume of water was swept over the palps. This phenomenon was supported by the fact that *P. australis* could not produce sufficient pseudofaeces, to modify the quality of ingested organic fractions, as shown by reduced compensation index values when *TPM* concentrations were high. Therefore, the production of pseudofaeces at high *TPM* concentration were used entirely to get rid of excess particles from the feeding apparatus. Bacon *et al.*, (1998) suggested that such a strategy may be associated with morphological constraints imposed by the feeding and

digestive process. Indeed, post-ingestive processes are more important than pre-ingestive selection for *M. arenaria*. If post-ingestive processes were important to *P. australis*, then this would be reflected in high organic absorption rates and absorption efficiency values, which was not observed in this study. Therefore, this study indicated that *P. australis* can only feed efficiently on low *TPM* concentration.

Furthermore, retention efficiency of different particles sizes may also contribute to the amount of energy absorbed if different particles sizes contained different quantity of organic materials. Defosse and Hawkins (1997) observed that *Mytilus edulis*, *Ruditapes philipinarum* and *Tapes decussatus* preferentially rejected as pseudofaeces particles within the range of 7.5 – 22.5 μm depending on the species and the conditions they were exposed to. In some turbid estuaries such as in the estuary of Marennes-Oleron, France (Barille *et al.*, 1997), finer grained sediments (3-6 μm) contain high organic contents, so Barille *et al.* (1997) speculated that turbid estuarine dwellers with a gill porosity in the 3-6 μm range would benefit greatly. However, the retention efficiency of finer particles has been shown to decrease with increasing concentration of clay and silt in natural seston (Barille *et al.*, 1993). Consequently, retention of high quality finer sediments may be reduced with negative selection as a result (Bacon *et al.*, 1998). In this study, particularly in experiment 2, organic content of different particles sizes are presumably similar due to the ashed nature of the sediment. Therefore, compensation indices in the absence of natural seston for each particles size would be the same. The differences in the observed compensation index values for *P. novaezelandiae* and *P. canaliculus* in this study were a reflection of organic materials contained in the natural seston. If particle sizes in the natural seston fall within the (unknown) ranges of selected

ingested materials then preferential selection was based on particles size. However, if a wide range of particle size existed in the natural seston then selection by *Pecten novaezelandiae*, *Perna canaliculus*, and *Paphies australis* was based on organic content or possibly other qualitative factors of the particles such as carbon and nitrogen (Ward and MacDonald, 1996) regardless of particle sizes. Thus, this would justify the need to characterise different particles sizes and their subsequent organic contents of natural seston that composed the diets of these bivalve species.

2.7.2 Effect of food concentration and quality on energetics

The important outcome of changes in feeding processes was to maximise the amount of ingested food material over a wide range of suspended sediment concentrations and qualities. Therefore, it would be expected that organic absorption rates and absorption efficiency would be elevated up to an optimum level at certain *TPM* concentration before decreasing. This optimum level may differ between individuals of same species due to size differences (Griffiths and King 1979 a, b; Navarro and Winter, 1982; Yukihiro *et al.*, 1998 a) or differ between bivalve species (Hawkins *et al.*, 1998; MacDonald *et al.*, 1998; Yukihiro *et al.*, 1998 b).

Previous workers have observed that absorption efficiency for the hard clam *Mercenaria mercenaria*, (Bricelj and Malouf, 1984) cockle *Cerastoderma edule*, (Iglesias *et al.*, 1992, 1996) clam *Mya arenaria*, (MacDonald *et al.*, 1998) scallop *Placopecten magellanicus*, (MacDonald *et al.*, 1998) increased with increasing food quality, but independent of food concentrations. This study showed similar trends only for *P.*

novaezelandiae and *P. australis* when exposed to decreasing levels of organic content as *TPM* concentration increased for both diet qualities. The reason behind this phenomenon has not been fully established. However, according to Barille *et al.*, (1997) negative or low values obtained for *AE* were associated with the contribution of endogenous materials in faecal losses such as enzymes or fragments of digestive epithelium which are not reabsorbed when bivalves are exposed to very low diet organic fraction which may exceed the gross *AE*. Whereas production of specific digestive enzymes meeting the needs of each bivalve species (Brock, 1989) would result in high *AE*. In addition, bacterial activities within the bivalve may facilitate the breakdown of detritus materials and therefore increase absorption (Crosby *et al.*, 1990).

Perna canaliculus displayed a different trend for *AE* compared to *Pecten novaezelandiae* and *Paphies australis*. The difference may be associated with the feeding behaviour of this species. As more organics were selected through production of pseudofaeces for ingestion, organic absorption rates increased and so the efficiency in organic absorption increased. Yet, the mechanism(s) responsible for regulating *AE* in response to food content is still unclear. Bayne *et al.* (1987) observed that gut passage time is positively correlated with *AE*, a function which depends on ingestion rate. However, this positive function decayed within weeks. Cranford (1995) speculates that because gut passage time is controlled by ingestion rates which can be altered immediately in response to food quality, an initial increase in gut passage time due to increase in ingestion may have contributed to the initial rapid increase in absorption efficiency.

Respiration rates between and within species were quite different when exposed to different diet quality. The differences may be due to a positive relationship between metabolic activities and feeding activities (Griffith and Griffith, 1988). Because *Pecten novaezelandiae* and *Perna canaliculus* generally have high clearance rates and pseudofaeces production rates when exposed to ashed sediments, respiration rates were also high. Inversely, when these species are exposed to high diet quality, the lower respiration rates were probably due to a reduction in feeding rates.

Other studies revealed that respiration rates for *Mytilus edulis* (Widdows *et al.*, 1979; Bayne *et al.*, 1993) and *Spisula subtruncata* (Molenberg and Kiorboe, 1981) were independent of food concentration and quality, while others showed that respiration rates for infaunal *Cerastoderma edule* (Navarro *et al.*, 1992 and 1994) and *Mya arenaria* (Grant and Thorpe, 1991; MacDonald *et al.*, 1998) were significantly affected by food concentration and quality. The decline in respiration rates noted by some workers (Grant and Thorpe, 1991) was considered as a mechanism to conserve energy. This is supported by the fact that the reduction in respiration rates for *P. canaliculus* and *P. novaezelandiae* when exposed to ashed and non-ashed sediments respectively, lead to consistence positive scope for growth regardless of *TPM* concentration. In addition, the similarities observed in scope for growth for *P. australis* is a reflection of metabolic activities as feeding rates were similar between the diet qualities. On the contrary, the high respiration rates observed for *P. canaliculus*, when exposed to high concentrations of ashed sediment, was a clear reflection of high feeding rates observed at these high *TPM* concentrations. Consequently, the bivalve received no benefit in terms of scope for growth, eventhough organic absorption rates were high at high *TPM* concentrations.

For most, scope for growth revealed a depressing effect of increased diet concentrations. These effects may be related to the fact that the species used in this study may eventually stop feeding at high *TPM* concentrations that provoke the clogging of their pallial organs (Barille *et al.*, 1997) and/or due to the fact that energy intake cannot meet the increasing demands of metabolic activities (Bayne and Newell, 1983). Therefore, positive scope for growth values attained for *Perna canaliculus* and *Pecten novaezelandiae* when exposed to non-ashed and ashed sediment would eventually take zero values if *TPM* concentrations increased further. Despite that, scope for growth was still positive even at high *TPM* concentrations (see results). Hawkins *et al.*, (1996) demonstrated that *Mytilus edulis* displayed positive net energy balance even at 80 mg l⁻¹ of natural seston. Similarly, scope for growth for *Crassostrea gigas* (Barille *et al.*, 1997) was positive until natural seston exceeded 150 mg l⁻¹. Therefore, the feeding strategies which include alteration of clearance rates, pre-ingestive selection through pseudofaeces production, a combination of both, post-ingestive mechanisms, or reduction in metabolic activities enable suspension filter-feeding bivalves to support growth in times of elevated food concentrations.

2.7.3 Comparison Between Feeding Rates and Energetics at 20 mg l⁻¹ Sediment

Added to Natural Seston

The feeding rates and energetics of *Pecten novaezelandiae* were not significantly different between the diets, except for respiration rates. The diet composed of different *POM* fraction but similar *TPM* concentration. Therefore, the similarity between the

responses indicated that scallops have the ability to counteract the depressing effect of lower *POM* fraction to obtain sufficient energy, similar to the amount of energy gained when the diet had higher *POM* fraction.

Clearance rates (*CR*) was only significantly different when *Perna canaliculus* was exposed to different *TPM* concentrations and *POM* fraction. Despite the differences in *CR*, the amount of energy gained were still similar. Perusal of the data (Fig 2.12a) showed that overall difference in clearance rate (the amount of water cleared of suspended particles per unit time) was only different by a small margin. A large difference would be reflected in the amount of energy gained. This phenomenon was observed in the feeding responses of *Paphies australis*, whose clearance rates were significantly different when exposed to different *TPM* concentrations. Consequently, lower energy was gained when *TPM* concentration was high. Again this supported the fact that the feeding responses and energetics of *P. australis* were greatly affected by high *TPM* concentration.

2.8 Conclusion

Pecten novaezelandiae and *Perna canaliculus* regulated the amount of energy intake by increasing clearance rates and pseudofaeces production, except when organic fraction is high as such production is unnecessary (Navarro *et al.*, 1992). Clearance rates and selection of organic materials through pseudofaeces production were higher when both species were exposed to ashed sediments than when exposed to non-ashed sediments. This gave the advantage of ingesting similar or at some point elevated organic fraction as *TPM* concentrations increased. However, the adverse consequence for some bivalves

such as *Perna canaliculus* when exposed to ashed sediments is a low scope for growth as more energy is lost through metabolic activities due to high feeding activities.

Paphies australis can only feed efficiently at low *TPM* concentrations ($39.0 \pm 23.8 \text{ mg l}^{-1}$ in experiment 1 and $20.1 \pm 3.6 \text{ mg l}^{-1}$ in experiment 2). Above these values pipis were unable to compensate for increased sediment concentration and therefore had very low scope for growth.

The most capable bivalves, judged by the amount of net energy gain (scope for growth), when exposed to a wide range of food concentrations with high food quality, were the mussels (*Perna canaliculus*) followed by the scallops (*Pecten novaezelandiae*), and the least tolerant were pipis (*Paphies australis*). Furthermore, when ashed sediments (low food quality) were utilised, *P. novaezelandiae* demonstrated beneficial strategies of compromising diet depression, enabling it to maintain relatively low but constant net energy gain over a wide range of *TPM* concentrations. *P. canaliculus* showed a logarithmic decrease in *SFG* exhibiting very low values at the highest diet concentration. Again, *P. australis* was the least tolerant species.

CHAPTER 3

Effects of Resuspended Sediments Caused by Dredging on Seston Concentration and Quality

3. 1. Introduction

Fine sediments comprise most of the materials in deepened navigational channels which have accumulated over time as a consequence of weakened water currents (Yell and Riddell, 1995; Healy and Roberts, 1997). Such sediments of fine particle size typically have low settling rates once resuspended when dredged. Their potential impacts on the ambient water quality, however, are strongly determined by relative concentration and quality in the water column (Kester *et al.*, 1983). These impacts include possible release of contaminants from the sediment to the aqueous phase and increase in turbidity (Kester *et al.*, 1983; Ryan, 1989; Yell and Riddell, 1995). In addition, fine sediments can be transported over considerable distances from the source (Jago *et al.*, 1993) affecting water quality in neighbouring areas.

Several studies undertaken on dredging have aimed to better understand the impact of contaminants released by dredge spoils and subsequent bioaccumulation (Young and Pearce, 1975; Davis 1983; Kester *et al.*, 1983; Ahlf and Munawar, 1988; Al-Madany *et al.*, 1991; Toumazis, 1995), impact of disposal on sediment bathymetry

(Harms, 1989; Mathew, 1997) or direct impact of disposal on benthic communities (Foster *et al.*, 1991; Wood, 1994). Some also sought ways to minimise negative impacts of dredged spoils on the marine ecosystem by considering various dredging and disposal methods (Yell and Riddell, 1995).

Despite numerous works on the impact of dredging, limited studies have focused on the effect of suspended sediment caused by dredging on natural seston concentration and quality. However, previous works have shown that the quality of natural seston can be influenced by the concentration and quality of resuspended sediments. Where resuspended sediment contains high concentrations of organic matter, resuspension might be considered beneficial as it might enhance the seston quality in terms of organic content to suspension feeders (Wainright, 1990). Inversely, high concentrations of inorganic matter might dilute the concentration of organic matter or phytoplankton in the water column (Grant *et al.* 1997) giving low quality.

This study aims to quantify the effect of suspended sediments caused by dredging on natural seston concentration and quality. The study was undertaken during an intensive maintenance dredging operation at Stella Passage, Port of Tauranga. Surficial black silt/mud in the passage are low in heavy metal concentrations, but have a high proportion of organic to inorganic material (Healy and Roberts, 1997).

The null hypothesis assumed that the organic content and concentration of natural seston were similar between the dredged zone and surrounding areas during and after dredging. The observed seston concentrations in terms of particulate organic matter (mg l^{-1}) and total pigment ($\mu\text{g l}^{-1}$), were used to interpret potential impacts of resuspended

sediment caused by dredging on seston concentration and quality from water samples collected at study sites.

3.2 Methods

3.2.1 Sample Collection

Water samples were collected on 10th November 1998 in Stella Passage using the Port of Tauranga survey boat. Sampling of four study sites (Fig 3.1) was performed during an ebb tide which coincided with dredging operations. One site (site 1) was located within the dredging zone. Two other sites, each located 200 metres downstream (site 2) and 200 metres upstream (site 3) from the dredge, while, a control site was located at 500 metres upstream (site 4). At each site surface and bottom (within 0.5 metres from sediment) water samples were collected. A 5-litre water sampling device attached to weight was used for collecting water samples.

Sampling was repeated three times over each site. The first samples were collected while dredging was in operation, while the latter two sampling periods occurred after dredging ceased. Sampling commenced at site 1 and finished at site 4. The time taken between each successive sampling was approximately 1 hour. Positions (Appendix A.3) fixing for each study site was provided by a global positioning system (GPS). Even though there was a slight displacement in positions during each successive sampling, results were grouped together according to the sites described above.

Three replicates of water samples were filtered on pre-ashed, weighed 45mm GF/C Whatman filters then washed with isotonic ammonium formate, dried at 80 °C for 24 hours, and weighed to give total particulate matter (*TPM*, mg l⁻¹). Particulate inorganic matter (*PIM*, mg l⁻¹) was determined after ashing at 480 °C for 12 hours. Particulate organic matter (*POM*, mg l⁻¹) represented the difference between *TPM* and *PIM*. Total pigment (chlorophyll *a* and phaeophytin *a*) analysis was performed on three replicates using fluorometric technique according to Arar and Collins (1997).

The particle size was determined by Malvern Instruments Mastersizer. However, a very low resolution due to low concentrations of particles observed in the samples suppressed further procedures, so the analysis was aborted.

3.2.2 Statistical Analysis

A one way ANOVA test using Minitab 10.51 was employed to test the following null hypotheses.

- H_{01} : The surface concentrations of total particulate matter (*TPM*) and particulate organic fraction (*POM* fraction) between the dredged site and adjacent sites were not significantly affected by dredging
- H_{02} : After dredging ceased the surface concentrations of *TPM* and *POM* (fraction) between the dredged site and adjacent sites were similar.
- H_{03} : The concentrations of *TPM* and *POM* (fraction) near the bottom, between the dredged site and adjacent sites were not significantly affected by dredging

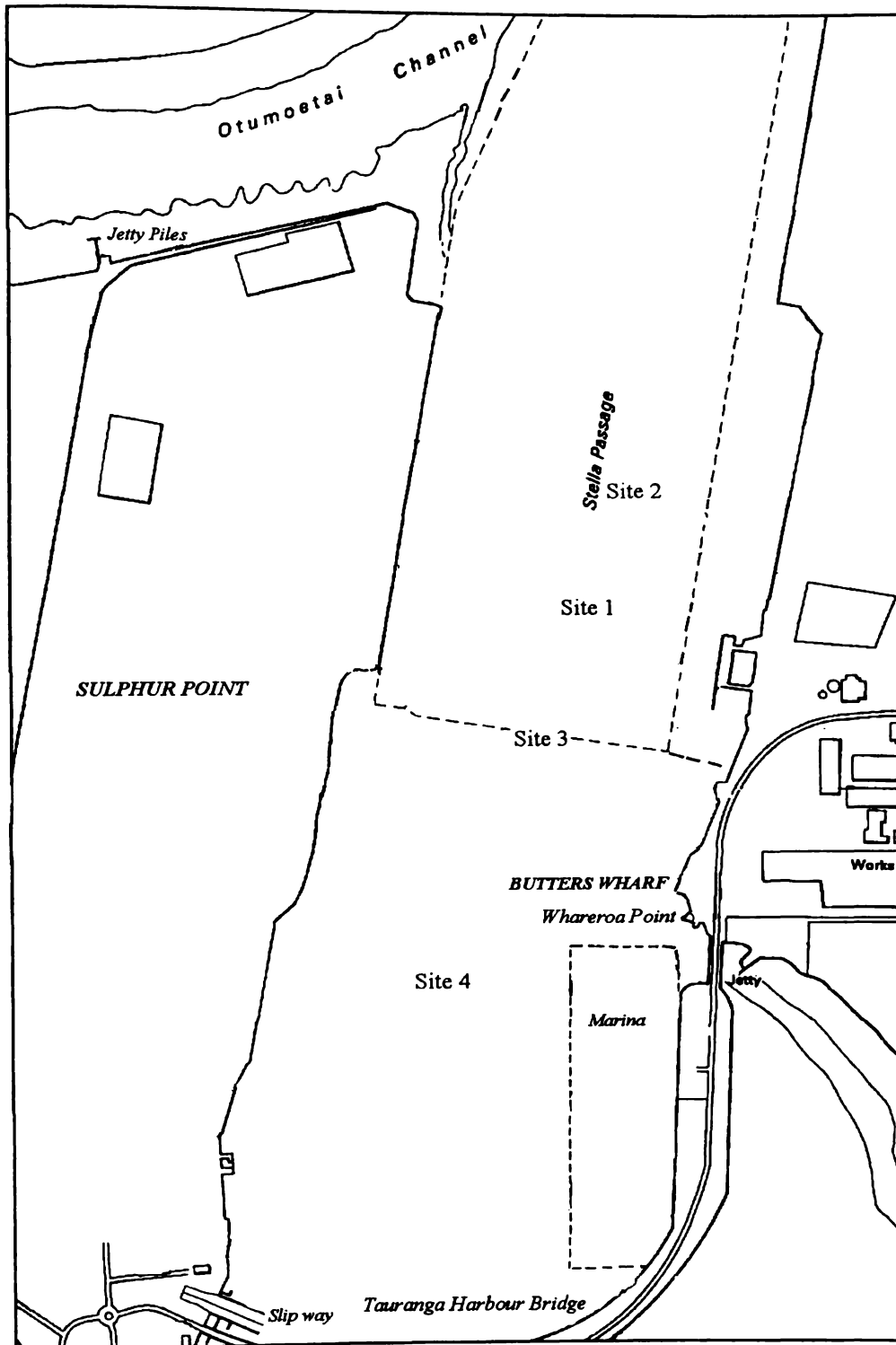


Figure 3.1 The positions of the study sites located within Stella Passage

H₀₄: After dredging ceased the concentrations of *TPM* and *POM* (fraction) near the bottom, between the dredged site and adjacent sites, were similar.

Data for *TPM* and *POM* were \log_{10} transformed prior to analysis to ensure normality and homogeneity of variance.

The data for total pigment deviated from normality or homogeneity even after transformation. Therefore, a non-parametric Kruskal-Wallis (K-W) procedure was employed to detect significant differences of total pigment ($\mu \text{ l}^{-1}$) between concentrations recorded at different sites and depths. A non-parametric *post hoc* Nemenyi test (Zar, 1996) similar to a Tukey test was employed to detect which means were different, if K-W test was significant. Concentrations recorded at different times for each depth were pooled together.

3.3 Results

3.3.1 Total Particulate Matter (*TPM*, mg l^{-1})

During dredging, time 1, (Fig. 3.2) the surface *TPM* concentration was significantly higher ($P < 0.001$) at the dredged site than sites 2, 3, and 4. Following the conclusion of the dredging operation, the concentration at the dredged site decreased from $9.67 (\pm 0.58) \text{ mg l}^{-1}$ during dredging to $3.33 (\pm 0.40) \text{ mg l}^{-1}$ at time 2. Concurrently, an increased in *TPM* concentration was observed between time 1 and 2 at 200 metres downstream from $2.77 (\pm 0.88)$ to $6.23 (\pm 0.76) \text{ mg l}^{-1}$. At time 3 *TPM* concentrations were constantly low at all sites. Despite that, the ANOVA test showed that *TPM* concentrations were significantly

different ($P < 0.001$) between sites. A Tukey test revealed that *TPM* concentrations were significantly higher at sites 1 and 4 compared to sites 2 and 3.

A different trend in *TPM* concentrations was observed close to the bottom. During dredging at time 1, the bottom *TPM* concentrations were not significantly different ($P > 0.05$) between sites. Despite that, the concentrations remained high at the dredged site even after the conclusion of the dredging operation, i.e. at time 2 and 3. The ANOVA test revealed that at time 3, the bottom *TPM* concentration at the dredged site was significantly higher ($P < 0.05$) compared to sites 2, 3, and 4.

3.3.2 Particulate Organic Matter (*POM*, mg l^{-1} and fraction)

The surface *POM* concentrations were $< 3 \text{ mg l}^{-1}$ at all sites (Fig 3.2), except at the dredged site during dredging (time 1), when *POM* concentration was $3.37 (\pm 0.32) \text{ mg l}^{-1}$. Despite that, the surface *POM* fractions (Fig 3.3) were significantly different ($P < 0.001$) between sites during dredging (time 1). A lower fraction was observed at the dredged site compared to sites 2, 3 and 4. In addition, the surface *POM* fraction decreased from $0.66 (\pm 0.08)$ to $0.30 (\pm 0.05)$ between dredging (time 1) and after dredging (time 2) at 200 metres downstream. At time 3 after dredging, the surface *POM* fractions were not significantly different ($P > 0.05$) from each other.

The bottom *POM* fractions (Fig 3.3) were not significantly different ($P > 0.05$) from each other during dredging nor after dredging, despite high *POM* concentrations (Fig 3.2) recorded at the dredged site (site 1) and at 200 metres downstream (site 2) during and after dredging.

3.3.3 Total Pigment ($\mu\text{g l}^{-1}$)

A Kruskal-Wallis test indicated that total pigments were significantly different ($P < 0.05$) between sites (Fig. 3.4a). Following a non-parametric *post hoc* test, the surface total pigment concentration at site 1 was lower compared to the bottom concentrations recorded at site 1 and 4. Despite that, the proportion of chlorophyll *a* to phaeophytin *a* (the breakdown product of chlorophyll *a*) were similar between all sites and depths (Fig 3.3b). The average ratio was $\cong 3.5:6.5$ (chlorophyll *a*:phaeophytin *a*).

Figure 3.2 Total particulate matter (TPM) and Particulate organic matter (POM) obtained at site 1 (dredged site), site 2 (200 metres downstream), site 3 (200 metres upstream), and site 4 (500 metres upstream) for surface and bottom depths. Data are the mean of 3 replicates (± 1 SD).

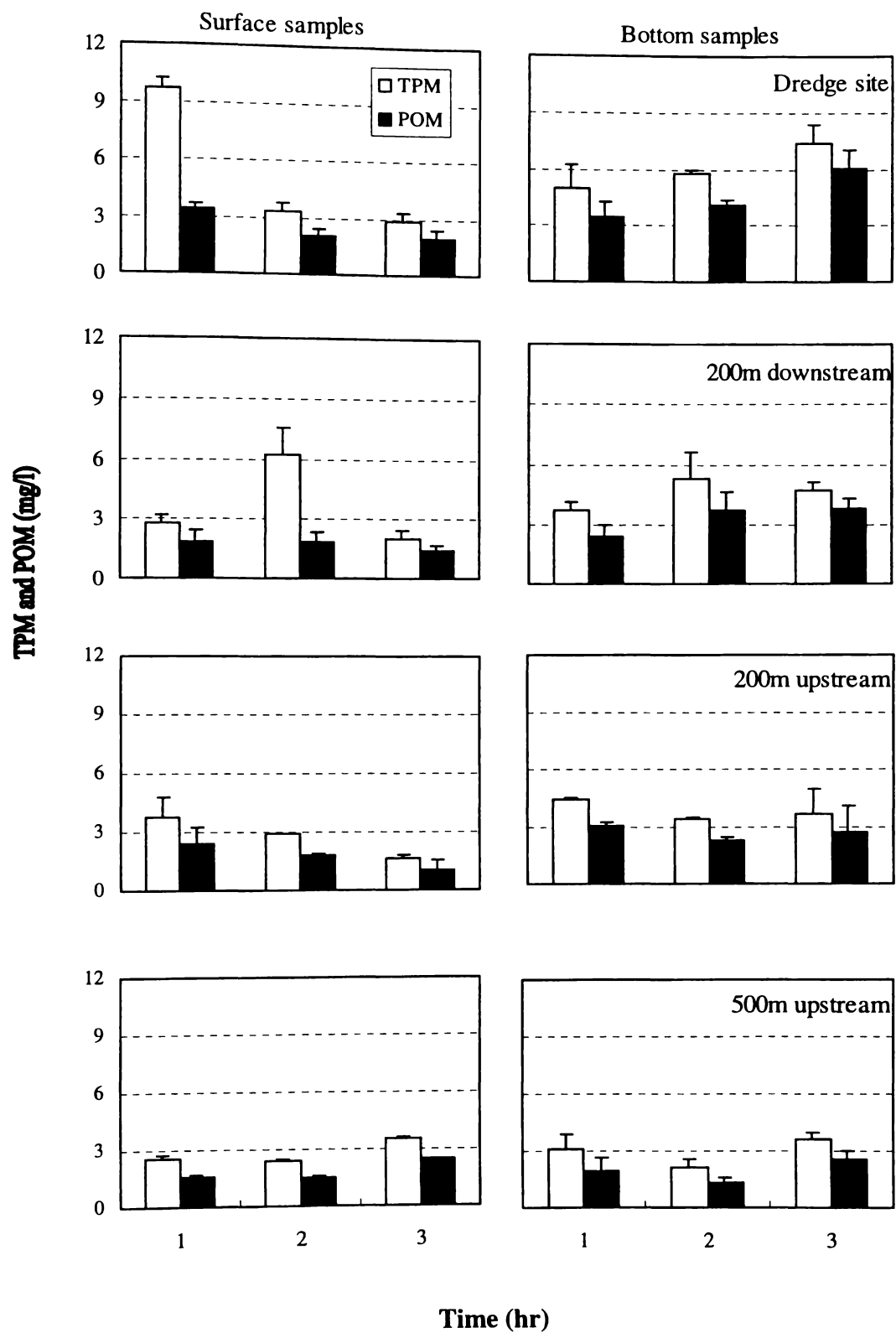
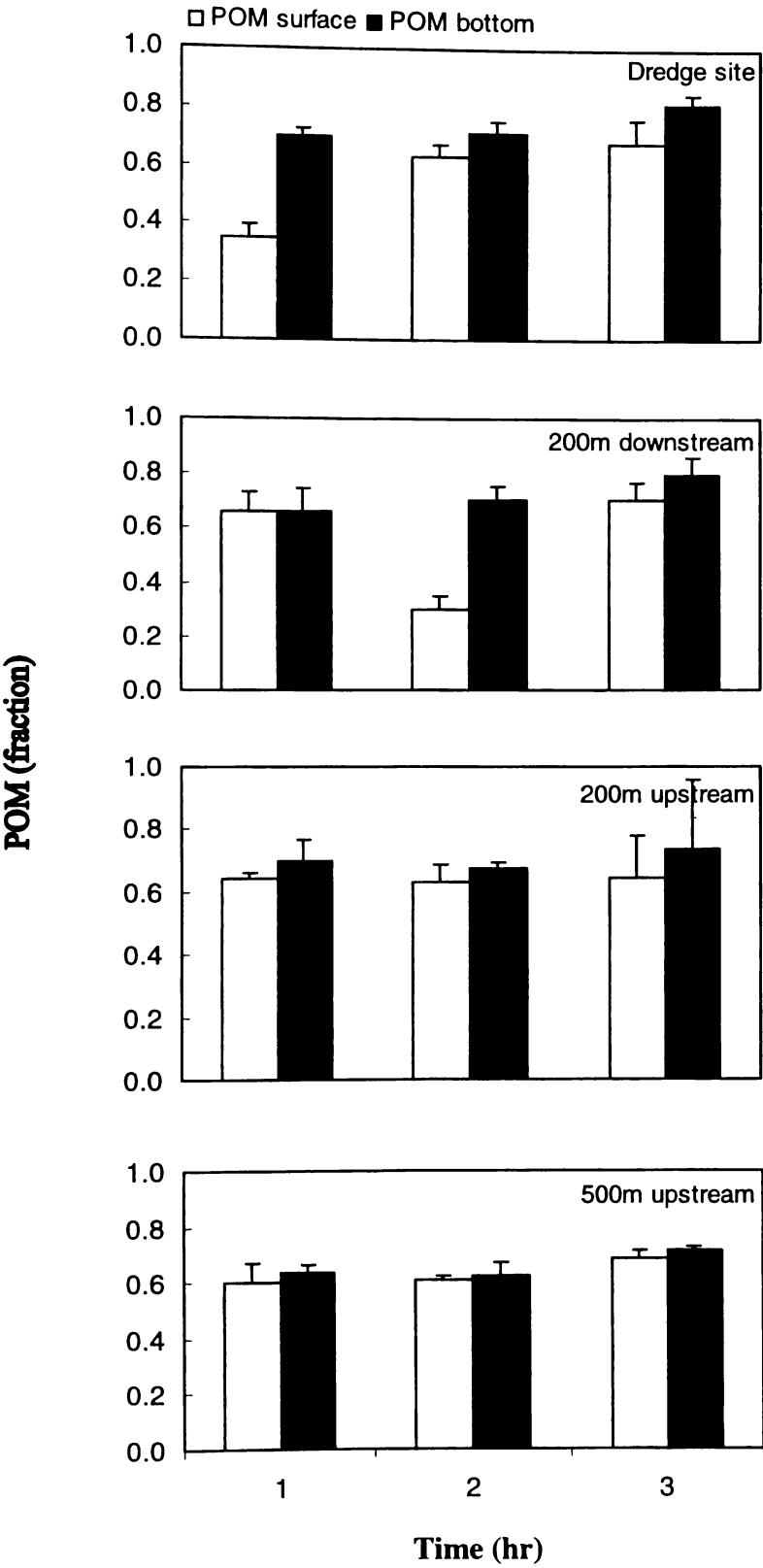


Figure 3.3 Particulate organic matter (fraction) obtained at site 1 (dredge site), site 2 (200m downstream), site 3 (200m upstream), and site 4 (500m upstream). Data are the mean of 3 replicates (± 1 SD).



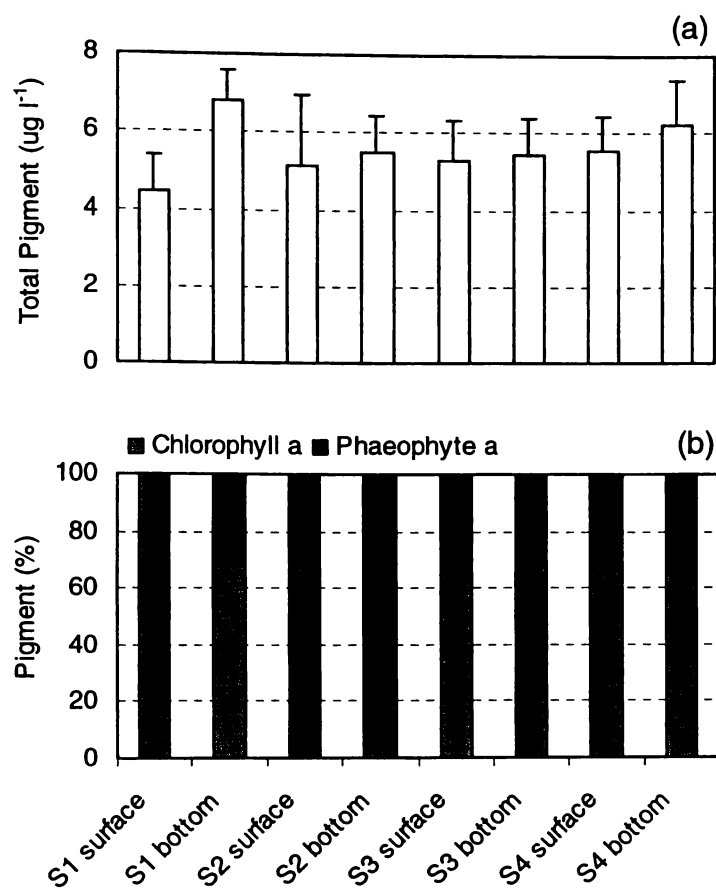


Figure 3.4 (a) Concentration of total pigment, and (b) percentage of chlorophyll *a* to phaeophytin *a*, obtained at the study sites. Data are the mean of 6 replicates (± 1 SD).

Table 3.1 Range of concentrations for total particulate matter, particulate organic fraction and total pigment encountered naturally during experiment 1 and 2.

Experiment	TPM (mg l ⁻¹)	POM (fraction)	Total pigment (µg l ⁻¹)
1	7.8 – 126.7	0.19 – 0.72	0.48 – 10.34
2	5.2 – 165.6	0.13 – 0.61	0.54 – 9.18

3.4 Discussion

The axis between the study sites was parallel to the ebb current direction. The water passing site 4 was carried directly to site 3 by ebb current. Since the dredging operation (site 1) was down stream, less variation in *TPM* and *POM* concentrations existed between site 3 and 4. However, water masses from the dredged site were carried directly to site 2 downstream. Therefore, the existence of significant horizontal differences in the means of *TPM* and *POM* measured were expected.

Ebb waters were dominated by waters coming from Waimapu estuary, Welcome Bay, Rangataua Bay, and Waipu Bay (Fig 1.1). The bulk of these water masses went under the Tauranga Harbour Bridge; yet, a portion of this water mass, especially from the Waipu Bay went through an opening adjacent to Whareroa point (Fig 3.1). The meeting of these water masses may have created a divergence in water movement resulting in resuspension of bottom sediment as seen by water discolouration (pers. obser.). Coupled with resuspended sediments from dredging, together these resuspensions may dilute the surface *POM* fraction at sites 1 and 2.

The *POM* fraction recorded in this survey were within, or in a few cases higher than, the ranges of *POM* fractions recorded for natural seston during the feeding experiments (Table 3.1). Similarly, the high resuspended matter recorded at the surface of site 1 may also affect the total pigment concentration by diluting it. This relationship was similar to other observations (Anderson and Meyer, 1986; Berg and Newell, 1986; Grant *et al.*, 1997) where a negative relationship existed between food concentrations and seston volume.

The volume of resuspended materials (*TPM*) recorded in this study did not exceed 10 mg l⁻¹, and it was comparatively less than natural seston used in the feeding experiments (Table 3.1). However, this comparison is limited only to the surface and bottom water samples. Therefore, getting more water samples representing other depths between the surface and bottom could yield a different *TPM* concentration. Nevertheless, resuspended sediments as measured in Nephelometric turbidity unit (NTU) by Kensington (1990) and Sander (1993) showed that high turbidity was recorded at the dredge and disposal sites but decreased rapidly within minutes after each activity. Kensington (1990) also found that, the turbidity levels were consistently higher at the bottom than at the surface over the dumping ground. Although, in this study, resuspension was caused by dredging, the results still show that the *TPM* concentration observed at the dredged site decreased rapidly, while the concentration at the bottom remained consistently high even three hours after dredging. Ebb currents played a significant role in the observed trends for at least with the surface values. Nevertheless, this result was limited to a 200 metres downstream.

This study indicated that resuspended sediment from dredging has limited impact on the local food quality in terms of organic content and total pigment concentration, for at least 200 metres downstream from the dredged zone, considering the level encountered naturally. The high organic content in the dredged sediments may have contributed to high organic values observed during dredging, limiting the impact of resuspension on seston quality. Thus getting more samples at other depths would probably yield similar results.

CHAPTER 4

Conclusions and Recommendations

Suspension feeding bivalves are often the dominant macrofauna in most benthic communities in estuaries and open coastal waters (Kautsky and Evans, 1987; Thouzeau *et al.*, 1991). They play a significant role as a coupling agent between the benthic and pelagic environments. Turbidity affects the feeding behaviour and energetics of bivalves, by either affecting the feeding apparatus (gills) directly, or indirectly by affecting the food quality. This study was undertaken to investigate some aspects of the relationship between turbidity and the feeding physiology and energetics of three New Zealand filter-feeding bivalves, scallops (*Pecten novaezelandiae*), mussels (*Perna canaliculus*), and pipis (*Paphies australis*). Secondly, it investigated the effect of resuspended sediment caused by dredging on seston concentration and quality. This chapter provides a brief summary of the main findings, discusses the implications of these findings, and provides suggestions for future study.

4.1 Summary of the Main Findings

1. The naturally occurring seston obtained from Tauranga Harbour used in the diet mixture fluctuated substantially in quality and quantity. The *TPM* concentration ranged from 5.2 - 165.6 mg l⁻¹. The utilisable food content of seston also fluctuated greatly, the *POM* content ranged between 13% - 72%, whereas total pigment (chlorophyll *a* plus phaeophytin *a*) concentration ranged from 0.48 - 10.34 µg l⁻¹.

2. *Pecten novaezelandiae* had a positive scope for growth until *TPM* increased beyond $\cong 190 \text{ mg l}^{-1}$. Net energy gain was accomplished by (1) selecting more nutritious particles for ingestion when *POM* content became diluted to $\leq 14\%$, and (2) reduction of energy expenditure through alteration of respiration losses. If the diet contained a high *POM* fraction, clearance rates (the volume of water swept clear of particles per unit time) decreased with increasing *TPM* concentration, but increased up to a limit (120-140 mg l^{-1}) when the diet had a lower *POM* content.

3. When the diet had a high *POM* content, *Perna canaliculus* supported growth by clearing less water, reducing the amount of particles rejected as pseudofaeces, and reducing the amount of energy expired through respiration. Consequently, *SFG* was uniformly high as *TPM* concentrations increased to 332 mg l^{-1} . Inversely, when the diet had a low *POM* content, *P. canaliculus* had higher clearance rates, and rejected more particles as pseudofaeces as *TPM* concentrations increased. Selection for nutritious particles occurred when the *POM* content was diluted to $\leq 16\%$ in both diet mixtures. As a consequence of high feeding rates, respiration rate also increased. Therefore, as *TPM* concentrations increased the balance between energy gain and expenditure produced low *SFG*.

4. *Paphies australis* generally had low clearance and rejection rates, and could only select higher nutritious particles at the lowest *TPM* concentrations in both experiments. As *TPM* concentrations increased beyond these low values (39 mg l^{-1} in experiment 1 and 20 mg l^{-1} in experiment 2), *SFG* decreased dramatically to almost zero.

5. When compared to natural variations, dredging had a limited effect on seston concentration and quality in the water column, within 200 metres up and downstream from the dredging operation.

4.2 Implications for Dredging Management

Resuspension of sediment is often associated with dredging operations. As the results of this study indicated, the effects of this sediment are not uniform on all suspension feeding bivalves, some can tolerate high suspended loads while others can not. By knowing the locations of benthic organisms, relative to the dredging site, as well as the organisms tolerance levels to suspended matter, then the allowable volume of resuspension that should not be exceeded during dredging operations can be evaluated. For example, high loads of suspended sediment may have no significant effect on high tolerance benthic organisms, therefore the volume may be kept high, and vice versa for intolerant species. In addition, sufficient knowledge on the general characteristics of the proposed dredged materials in terms of utilisable food level such as organic content, and contaminant levels are also essential. If the sediments contain high organic content, and less contaminant levels, then high resuspension may enhance the quality of seston and ultimately have beneficial effects on the affected marine biota. By integrating these concepts into dredging management, then any deleterious effect on the adjacent biota may be minimised.

The results also showed that no dead bivalve was reported during the experiments, even though they were exposed to suspended sediment for 8 hours. This indicates that these bivalves can recover from periodic exposure to high turbidity. Since resuspended sediment caused by dredging operations typically remains in the

water column less than 8 hours, it can be assumed that these bivalves can fully recover after being exposed to this type of resuspension. Nevertheless, these results are only limited to bivalve being exposed to fine suspended sediments, but not to inundation and blanketing by settling particles.

4.3 Recommendations for Future Studies

The relationship between seston characteristics and bivalve feeding behaviour is based on limited data relating to Tauranga Harbour sediments and certain bivalve species (scallops, mussels, and pipis). The generality of these relationships could be enhanced if more studies are undertaken. The following studies are recommended.

1. Investigation of the seston concentration and quality over the natural bivalve populations. This will provide knowledge on the seston characteristics to which bivalve populations are naturally exposed.
2. Characterisation of the seston component in terms of particles sizes and their subsequent quality (such as organic, carbon, nitrogen, lipid and protein) as bivalves may rely on a particular particle size for food.
3. Exposing the bivalve species to increasing levels of suspended sediments for a longer period, thus establishing a relationship between the variables on a long-term basis. This will provide a better understanding of the tolerance capacity of certain bivalve species which can thrive on persistent high load of sediments commonly encountered in estuaries, open coastal waters and near outfall areas.

4. Determination of the amount of nutrients taken up and released to the water column by bivalves over a wide range of seston concentrations. This has a potential effect on other marine populations and general ecology of the Harbour, since bivalves have been known as coupling agents between the benthic and pelagic environments.

Appendix

- A.1 Particle sizes of non-ashed sediment used in the first feeding experiment in May 1997, and part of the second experiment in September 1997

MASTERSIZER

Result: Analysis Report

Sample ID: 15D
Sample File: MISC
Sample Path: A:\
Sample Notes: Non-ashed Sediment

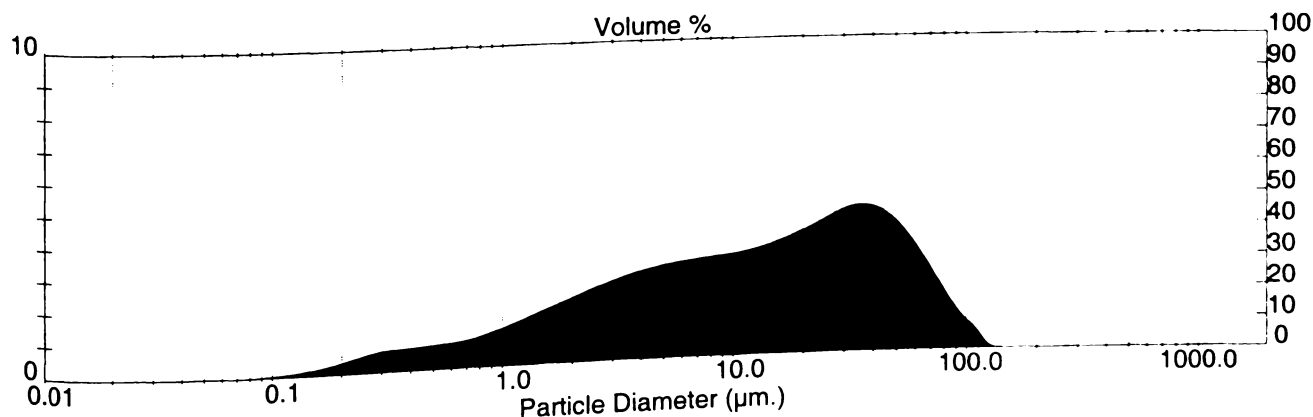
Sample Details
Run Number: 2
Record Number: 16

Measured: Sun, Feb 07, 1999 3:14PM
Analysed: Sun, Feb 07, 1999 3:14PM
Result Source: Analysed

System Details
Range Lens: 300RF mm Beam Length: 2.40 mm Sampler: MS17 Obscuration: 21.8 %
Presentation: 3OHD [Particle R.I. = (1.5295, 0.1000); Dispersant R.I. = 1.3300] Residual: 0.600 %
Analysis Model: Polydisperse
Modifications: None

Result Statistics
Distribution Type: Volume Concentration = 0.0143 %Vol Density = 2.650 g / cub. cm Specific S.A. = 0.8606 sq. m / g
Mean Diameters: D (v, 0.1) = 1.15 um D (v, 0.5) = 12.37 um D (v, 0.9) = 54.59 um
D [4, 3] = 21.23 um D [3, 2] = 2.63 um Span = 4.321E+00 Uniformity = 1.362E+00

Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.00	0.06	0.00	6.63	3.10	7.72	40.06
0.06	0.01	0.07	0.01	7.72	3.15	9.00	43.22
0.07	0.01	0.08	0.03	9.00	3.21	10.48	46.43
0.08	0.03	0.09	0.05	10.48	3.29	12.21	49.72
0.09	0.05	0.11	0.10	12.21	3.40	14.22	53.12
0.11	0.08	0.13	0.19	14.22	3.55	16.57	56.67
0.13	0.14	0.15	0.32	16.57	3.74	19.31	60.41
0.15	0.21	0.17	0.53	19.31	3.96	22.49	64.37
0.17	0.31	0.20	0.84	22.49	4.21	26.20	68.57
0.20	0.42	0.23	1.26	26.20	4.46	30.53	73.03
0.23	0.54	0.27	1.81	30.53	4.63	35.56	77.66
0.27	0.64	0.31	2.45	35.56	4.64	41.43	82.30
0.31	0.70	0.36	3.15	41.43	4.44	48.27	86.73
0.36	0.72	0.42	3.87	48.27	4.00	56.23	90.73
0.42	0.75	0.49	4.62	56.23	3.34	65.51	94.07
0.49	0.79	0.58	5.41	65.51	2.55	76.32	96.63
0.58	0.82	0.67	6.23	76.32	1.75	88.91	98.38
0.67	0.89	0.78	7.12	88.91	1.05	103.58	99.43
0.78	1.02	0.91	8.14	103.58	0.54	120.67	99.97
0.91	1.17	1.06	9.32	120.67	0.03	140.58	100.00
1.06	1.34	1.24	10.66	140.58	0.00	163.77	100.00
1.24	1.53	1.44	12.19	163.77	0.00	190.80	100.00
1.44	1.72	1.68	13.92	190.80	0.00	222.28	100.00
1.68	1.91	1.95	15.83	222.28	0.00	258.95	100.00
1.95	2.10	2.28	17.93	258.95	0.00	301.68	100.00
2.28	2.29	2.65	20.21	301.68	0.00	351.46	100.00
2.65	2.46	3.09	22.67	351.46	0.00	409.45	100.00
3.09	2.62	3.60	25.29	409.45	0.00	477.01	100.00
3.60	2.76	4.19	28.06	477.01	0.00	555.71	100.00
4.19	2.88	4.88	30.94	555.71	0.00	647.41	100.00
4.88	2.98	5.69	33.91	647.41	0.00	754.23	100.00
5.69	3.05	6.63	36.96	754.23	0.00	878.67	100.00



Mastersizer S long bed Ver. 2.14
Serial Number:

A.2 Particle sizes of ashed sediment used during the second feeding experiment in September 1997



MASTERSIZER

Result: Analysis Report

Sample ID: 5E
Sample File: MISC
Sample Path: A:\
Sample Notes: Ashed Sediment

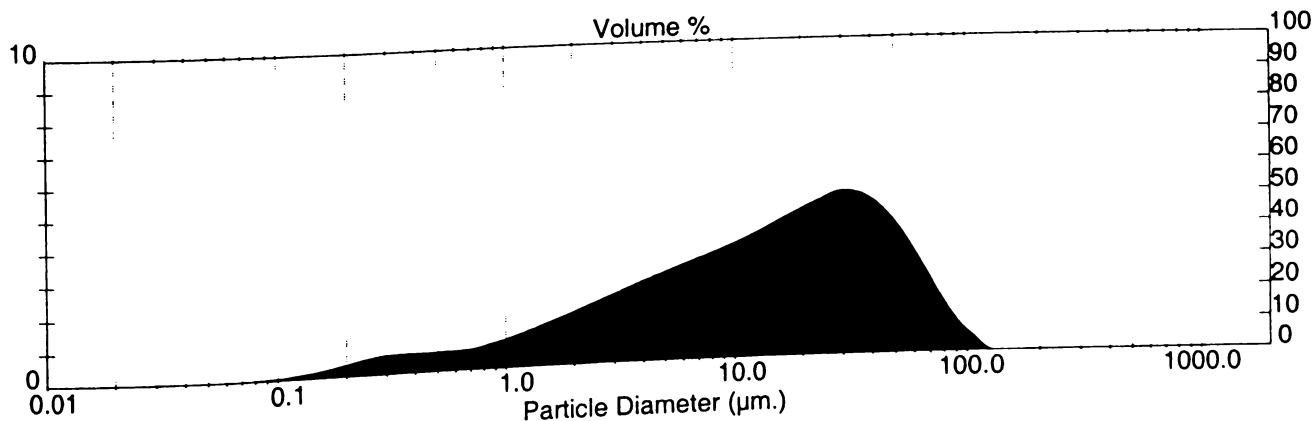
Sample Details
Run Number: 1
Record Number: 15

Measured: Sun, Feb 07, 1999 3:09PM
Analysed: Sun, Feb 07, 1999 3:09PM
Result Source: Analysed

System Details
Range Lens: 300RF mm Beam Length: 2.40 mm Sampler: MS17 Obscuration: 20.2 %
Presentation: 3OHD [Particle R.I. = (1.5295, 0.1000); Dispersant R.I. = 1.3300] Residual: 0.587 %
Analysis Model: Polydisperse
Modifications: None

Result Statistics
Distribution Type: Volume Concentration = 0.0149 %Vol Density = 2.650 g / cub. cm Specific S.A. = 0.8179 sq. m / g
Mean Diameters: D (v, 0.1) = 1.36 um D (v, 0.5) = 14.17 um D (v, 0.9) = 52.01 um
D [4, 3] = 21.29 um D [3, 2] = 2.77 um Span = 3.573E+00 Uniformity = 1.126E+00

Size Low (um)	In %	Size High (um)	Under%	Size Low (um)	In %	Size High (um)	Under%
0.05	0.01	0.06	0.01	6.63	3.17	7.72	35.52
0.06	0.01	0.07	0.02	7.72	3.35	9.00	38.87
0.07	0.02	0.08	0.04	9.00	3.53	10.48	42.40
0.08	0.04	0.09	0.08	10.48	3.74	12.21	46.14
0.09	0.07	0.11	0.15	12.21	3.96	14.22	50.09
0.11	0.11	0.13	0.27	14.22	4.19	16.57	54.29
0.13	0.17	0.15	0.44	16.57	4.44	19.31	58.72
0.15	0.25	0.17	0.69	19.31	4.67	22.49	63.40
0.17	0.34	0.20	1.03	22.49	4.89	26.20	68.29
0.20	0.44	0.23	1.47	26.20	5.10	30.53	73.39
0.23	0.54	0.27	2.00	30.53	5.11	35.56	78.50
0.27	0.61	0.31	2.61	35.56	4.94	41.43	83.44
0.31	0.64	0.36	3.25	41.43	4.55	48.27	87.99
0.36	0.63	0.42	3.88	48.27	3.94	56.23	91.92
0.42	0.63	0.49	4.51	56.23	3.16	65.51	95.08
0.49	0.64	0.58	5.15	65.51	2.30	76.32	97.38
0.58	0.64	0.67	5.80	76.32	1.48	88.91	98.86
0.67	0.68	0.78	6.48	88.91	0.80	103.58	99.66
0.78	0.79	0.91	7.27	103.58	0.34	120.67	100.00
0.91	0.91	1.06	8.18	120.67	0.00	140.58	100.00
1.06	1.05	1.24	9.23	140.58	0.00	163.77	100.00
1.24	1.21	1.44	10.44	163.77	0.00	190.80	100.00
1.44	1.38	1.68	11.82	190.80	0.00	222.28	100.00
1.68	1.55	1.95	13.37	222.28	0.00	258.95	100.00
1.95	1.73	2.28	15.10	258.95	0.00	301.68	100.00
2.28	1.91	2.65	17.02	301.68	0.00	351.46	100.00
2.65	2.10	3.09	19.12	351.46	0.00	409.45	100.00
3.09	2.29	3.60	21.40	409.45	0.00	477.01	100.00
3.60	2.47	4.19	23.87	477.01	0.00	555.71	100.00
4.19	2.65	4.88	26.53	555.71	0.00	647.41	100.00
4.88	2.83	5.69	29.35	647.41	0.00	754.23	100.00
5.69	3.00	6.63	32.35	754.23	0.00	878.67	100.00



A.3 Positions of the study sites recorded during water sampling within Stella Passage

Sites	time	GPS readings
1	1	274 535 °E
		710 511 °N
	2	274 535 °E
		710 511 °N
	3	274 546 °E
		710 500 °N
2	1	274 584 °E
		710 707 °N
	2	274 580 °E
		710 672 °N
	3	274 627 °E
		710 707 °N
3	1	274 303 °E
		710 303 °N
	2	274 440 °E
		710 311 °N
	3	274 443 °E
		710 268 °N
4	1	274 370 °E
		709 982 °N
	2	274 394 °E
		709 999 °N
	3	274 334 °E
		709 986 °N

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