ACOUSTIC SEABED CLASSIFICATION OF DEMERSAL CAPELIN SPAWNING HABITAT IN COASTAL NORTHEAST NEWFOUNDLAND

CANDACE ROSE-TAYLOR

ACOUSTIC SEABED CLASSIFICATION OF DEMERSAL CAPELIN SPAWNING HABITAT IN COASTAL NORTHEAST NEWFOUNDLAND

by

© Candace Rose-Taylor

A thesis submitted to the
School of Graduate Studies
in partial fulfilment of the
requirements for the degree of
Masters of Science

Geography
Memorial University of Newfoundland
May 2006
St. John's Newfoundland

Abstract

In this study, acoustic remote sensing tools and techniques were used to map, classify and characterize demersal (off beach) capelin (*Mallotus villosus,* Müller, 1776) spawning.

Historically, capelin are known to spawn on and near modern gravel beaches in coastal Newfoundland and demersally on the Southeast Shoal on the Grand Banks. Recently, capelin were observed spawning demersally at seven sites on the northeast coast of Newfoundland. These demersal sites were compared to previously studied beach sites around Newfoundland. Sea water temperature was determined to be the primary factor controlling the occurrence of capelin spawning. Spawning can occur on beaches or demersally when sea water temperatures are between 2°C and 12°C. Depth and temperature are highly correlated such that the depth of the capelin spawning sites was dependent on the depth of the 2°C to 12°C isotherms.

The second factor that controls capelin spawning is seafloor sediment. Beach and demersal spawning occurred on poorly-sorted postglacial sand and gravel sediments at water depths of 18 m to 33 m. The postglacial sediments from these sites are linked to changes in sea-level and may have been deposited around 8600 (radiocarbon) years ago when the postglacial lowstand of the sea-level of the study area was situated 17-18 m below present sea-level.

Supervised acoustic classification identified four different seabed types: fine sand, gravel (a mixture of medium sand to coarse pebble), cobble-boulder-bedrock, and macroalgae. Capelin spawning at most sites occurred on gravel, but at two sites spawning was associated with fine sand. The supervised acoustic classification of the

seabed was achieved by matching acoustic signatures to ground-truth data from grab samples and images captured with a remotely operated vehicle (ROV) equipped with a video camera.

Acknowledgements

First and foremost, I would like to thank my supervisor, Dr. John T. Anderson, for all his assistance, support, patience and continual encouragement throughout this thesis.

I would also like to thanks my co-supervisor, Dr. Trevor Bell, for his guidance and advice in writing my thesis, and Dr. Evan Edinger, the other member of my supervisory committee, for his enthusiasm and encouragement.

I am grateful to Dan Porter, Paulette Penton, Gail Davoren, the crews of the Canadian Coast Guard Ship (CCGS) *Shamook* and the commercial fishing vessel *Lady Easton II* for all of their help collecting data and samples in the field. Thanks are due to Vanessa Sutton, Greg Redmond, Denis Davis, and Chris Lang for their help with various analytical software and equipment. I would also like to thank the National Science and Engineering Council of Canada (NSERC) Strategic Grants Program, Memorial University of Newfoundland (MUN) Department of Geography, MUN School of Graduate Studies, MUN Faculty of Science, MUN Graduate Students' Union, and Department of Fisheries and Oceans Canada (DFO) for their financial support throughout the duration of this project.

Finally, I would like to thank all the members of the NSERC Strategic Project. It has been a great experience to be part of this large and diverse research group.

Table of Contents

List of Tables

List of Figures

List of Appendices

Glossary

Acoustic Class:	Acoustically distinct seabed.
Backscatter:	Reflection of the emitted sound energy. The shape and amount of energy returned is determined by structure and composition of the target substrate.
Echo sounder:	A tool that transmits sound energy through the water column. The returning signal or echo contains information on water depth and the characteristics of the seabed based on the amount of energy absorbed and reflected and the way in which the sounds is reflected.
Ping:	The complete cycle of transmission of an acoustic signal from the echo sounder through the transducer and reflection back to the transducer from the seabed.
Ping rate:	Number of pings emitted per second.
Signal to noise ratio:	The ratio of desired sound to undesired background noise.
Transducer:	A device that converts electrical energy into acoustic energy and vice versa.
Year-class abundance:	Number of fish spawned and hatched in a given year.

1. Introduction

1.1. Overview

The purpose of this study is to use acoustic remote sensing tools and techniques to classify and map demersal capelin spawning habitat in the Atlantic Ocean (Figure 1-1) along the northeast coast of Newfoundland (Figure 1-2). The second goal is to characterize the spawning habitats by temperature range, sediment size range, and bathymetric structure. These data will be used as a template for identifying additional demersal spawning areas.

Capelin (*Mallotus villosus,* Müller, 1776) (Figure 1-3) are a cold water species that is found throughout the Northern Hemisphere Circumpolar Region. The largest populations occur in the Bering Sea, the Barents Sea, and in the waters around Iceland, Greenland, and the Labrador Sea off the coast of Newfoundland and Labrador (Figure 1-1) (Carscadden and Vilhjalmsson, 2002). Although capelin are generally known to spawn either on beaches or in the nearshore (demersal), they spawn in both habitats in Newfoundland (Carscadden et al., 1989; Davoren et al., 2006). While beach spawning has been widely studied (Nakashima and Wheeler, 2002; Templeman, 1948), far less work has been done on demersal spawning and its associated habitats in Newfoundland, most likely due to site inaccessibility (Carscadden et al., 1989; Nakashima and Wheeler, 2002; Templeman, 1948). In previous studies, demersal capelin spawning habitats were characterized using SCUBA, underwater video, bottom grabs and through analyses of stomach contents of fish caught by bottom trawling (Carscadden et al., 1989; Nakashima and Wheeler, 2002; Saetre and Gjosaeter, 1975; Thors, 1981). The present study is the first to use acoustics to map and classify demersal capelin spawning habitats. This thesis

Figure 1-1: Map of the circumpolar Arctic region.

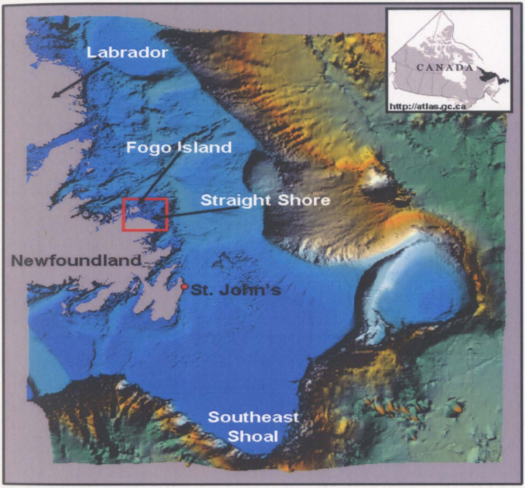

Figure 1-2: Map of Newfoundland and Labrador and the surrounding seafloor. The red square indicates the study area, Northeast Newfoundland and the Straight Shore.

Figure 1-3: Capelin (*Mallotus villosus*, Müller, 1776)

is one component of a National Science and Engineering Research Council of Canada (NSERC) Strategic Project that aims to gain a better understanding of the environmental conditions that influence capelin recruitment and ecology. The work done through this study and the NSERC Project will help to identify, understand, and map demersal capelin spawning habitats so that they may be conserved for future spawning.

1.2. Acoustic seabed mapping and classification

Acoustic seabed classification is based on systematic analysis of backscatter signals (also known as echo traces) (Collins and Rhynas, 1998; Preston et al., 2004). The seabed characteristics that have the greatest influence on signal response are sediment properties such as grain-size, porosity, seabed roughness (including sedimentary bedforms and bedrock outcrops), and the presence of flora and fauna on or in the seabed (Collins, 1999). A smooth, soft, simple (homogeneous) substrate such as mud will absorb most of the sound energy, producing a delayed and short signal return or low backscatter. In contrast, a rough, hard, complex substrate such as poorly-sorted gravel will reflect most of the transmitted energy resulting in a nearly immediate and long return signal or high backscatter (Figure 1-4) (Collins, 1999; Quester Tangent Corporation, 2004).

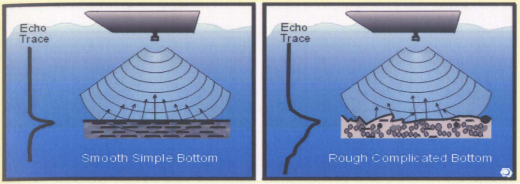

Figure 1-4: Eco-trace shape for a smooth simple seabed and for a rough complicated (hard and poorly-sorted) seabed (Quester Tangent Corporation, 2004).

Normal incidence acoustic systems coupled with Quester Tangent Corporation (QTC) seabed classification software have been used to identify and map seabed features such as sediment grain-size, benthic habitats and slope (Anderson, 2001; Freitas et al., 2001; Freitas et al., 2003a; Freitas et al., 2003b; Hutin et al., 2005; von Szalay and McConnaughey, 2002). Anderson (2001) successfully classified marine habitats in coastal Newfoundland using normal incidence acoustic echo sounders with QTC classification software.

1.2.1. Normal incidence acoustics

Normal incidence acoustic echo sounders provide information on the relative characteristics of the seabed. The transducer emits a sound pulse at a frequency typically between 30 and 200 kHz, and the return signal of echo is reflected from the seabed back to the transducer (Kenny et al., 2003). These single beam echo sounders generate data from a relatively small footprint on the seabed, and therefore significant interpolation is required in order to determine the characteristic features of the seabed. The acoustic footprint depends on the beam angle, ping rate, and depth of the seabed (Kenny et al., 2003). As depth increases the beam angle and footprint increase but the resolution decreases; conversely, as the depth decreases, the beam angle and the size of the footprint is reduced but the resolution is increased (Figure 1-5).

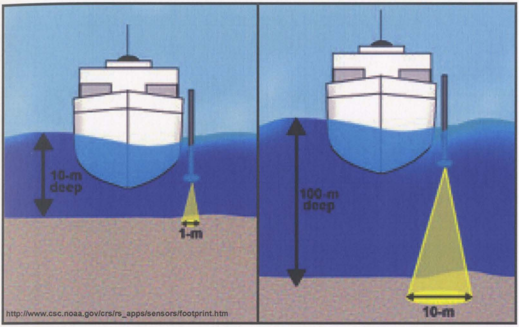

Figure 1-5: Change in beam angle and size of acoustic footprint with change in depth.

1.2.2. QTC IMPACT

QTC IMPACT is a commercial bottom classification software package that analyzes acoustic data generated by normal incidence echo sounders (Preston et al., 2004). The QTC IMPACT software organizes the acoustic echoes from the seabed into distinct groups based on the shape of the echo trace, also referred to as the acoustic signature. This is achieved by one of two methods; either an unsupervised classification or a supervised classification (Collins and Lacroix, 1997). The approach taken depends on the availability of ground-truth data. Unsupervised classification is most appropriate when there is little or no ground-truth data. In this case the acoustic signatures or classes cannot be assigned to a specific seabed type (Collins, 1999; Collins and Lacroix, 1997). Ground-truth data are required for supervised classification so that acoustic classes can be assigned to previously described seabed types (Collins, 1999; Collins and Lacroix, 1997). The unsupervised and supervised classifications are further described in the methods section of this thesis.

1.3. Capelin biology

Capelin Biology

Capelin are small pelagic schooling fish from the family Osmeridae (Carscadden et al., 2001; Carscadden and Vilhjalmsson, 2002; Davoren et al., 2006). Capelin are a key forage species and are important to the diet of large piscivores such as seals, whales, birds, and fish including Atlantic cod (Davoren et al., 2006). They are a short-lived species, maturing after three or four years. It is these mature fish that constitute the spawning population (Carscadden et al., 2001).

Spawning migrations

Capelin in the Northwest Atlantic Ocean overwinter near the continental shelf edge then they mature in the spring and migrate inshore to spawn (Davoren et al., 2006). Capelin may migrate across the Newfoundland Shelf via deep water trenches because this is the route taken by their main predator, Atlantic cod (Davoren et al., 2006; Rose, 1993). The trenches are in the warm bottom layer (water temperature $>0^{\circ}C$) and below the cold intermediate layer (CIL), water with temperatures $<0^{\circ}C$, thus they provide a warm water refuge which may help to accelerate maturation in preparation for spawning (Colbourne et al., 1997b; Davoren et al., 2006; Shackell et al., 1994a).

Spawning behaviour

As capelin approach spawning, they become sexually dimorphic. Males show the most morphological change by developing enlarged pectoral and anal fins (Figure 1-6). Scales along the lateral line also become enlarged (Figure 1-6). Females are distinguished from the males because they lack secondary sex characteristics and they have a distended, egg-filled abdomen (Figure 1-7) (Carscadden and Vilhjalmsson, 2002). Capelin separate into sex-specific schools (Jangaard, 1974). Ripe males move into areas suitable for spawning where they stay to release their milt numerous times during the course of the spawning event (Davoren et al., 2006; Jangaard, 1974). Female schools stay offshore in deep water for several weeks and they remain fairly inactive as they ripen. After ripening, the females move into the spawning area to join the males where

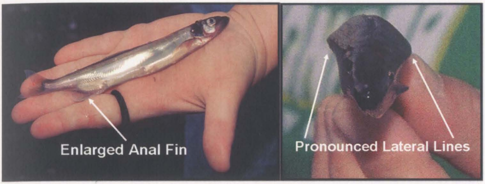

Figure 1-6: Male capelin at spawning stage with enlarged anal fin and enlarged scales along the lateral lines.

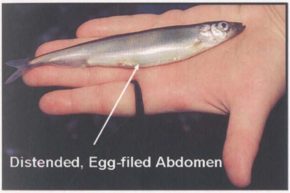

Figure 1-7: Female capelin at spawning stage with distended egg-filled abdomen.

they release all their eggs (Davoren et al., 2006; Jangaard, 1974; Saetre and Gjosaeter, 1975; Vilhjalmsson, 1994). Traditionally, it was understood that capelin spawn only once because a large number had been observed dead or stranded on the beach or floating on the surface of the water after spawning. Recent studies, however, show that some females survive to a second spawning season (Carscadden et al., 2001; Carscadden and Vilhjalmsson, 2002; Jangaard, 1974; Shackell et al., 1994b).

Spawning habitat

Capelin spawning habitat varies throughout the Northern Hemisphere Circumpolar Region (Table 1-1). Capelin spawn in water temperatures between 1.5°C and 14.0°C, in 0 m to 280 m water depth, and on substrate that ranges between 0.1 mm and 15 mm diameter in size (Table 1-1). Carscadden et al. (1989) described demersal spawning on the Southeast Shoal (Figure 1-2), a site more than 350 km from the Newfoundland coast and in 40 to 80 m water depth (Table 1-1). During the last glaciation (the late Wisconsinan), the Southeast Shoal was believed to have remained unglaciated but had emerged from the sea, due to eustatic sea-level lowering (Carscadden et al., 1989). The postglacial rise in eustatic sea-level has subsequently submerged the Southeast Shoal so Carscadden et al. (1989) suggest that the capelin that currently spawn demersally on the Southeast Shoal were once beach spawners.

Seawater temperature has been cited as an important factor controlling capelin spawning(Carscadden et al., 2001; Carscadden et al., 1989; Davoren et al., 2006; Nakashima and Wheeler, 2002; Templeman, 1948). In Newfoundland, capelin typically

Table 1-1: Water temperature, depth and substrate grain-size used for spawning by major capelin populations in the Northern Hemisphere.

Location	Water Temperature (°C)	Water Depth (m)	Substrate grain size (mm)	Source
			Beach	
Alaska	5-10		2-20	Pahlke (1985)
West Greenland	1.9-8.5		n/a	Vilhjalmsson (1994)
Newfoundland	2.5-11.9		2-15	Andrews (2005) Carscadden et al. (1989) Nakashima and Wheeler (2002) Templeman (1948)
			Demersal	
Southeast Shoal, Newfoundland	0.1-6.3	40-80	0.5-2.2	Carscadden et al. (1989) Thors (1981)
Murman, Norway	1.5-6.5	10-280	5-15	Vilhjalmsson (1994) Thors (1981)
Iceland	5.0-7.0	5-90	0.1-4.0	Vilhjalmsson (1994)

spawn on beaches at seawater temperatures between 2.5°C and 10.8°C (Carscadden et al., 2001; Carscadden et al., 1989), whereas demersal spawning on the Southeast Shoal occurred at temperatures as low as 0.1°C (Table 1-1), the lowest reported temperature for capelin spawning. At Bellevue Beach in Newfoundland, spawning ceased when surface water temperatures exceeded 12°C (Carscadden et al., 2001). Other studies have shown that demersal spawning sites are used only when water temperatures on the beach become too high for capelin to spawn (Carscadden et al., 1989; Nakashima and Taggart, 2002; Templeman, 1948). Results from Bellevue Beach suggest that off-beach (demersal) spawning sites may make a negligible contribution to the overall capelin population (Nakashima and Taggart, 2002).

Historically, capelin in coastal Newfoundland spawned on beaches in June (Carscadden et al., 2001; Davoren et al., 2006; Templeman, 1948). In the 1990s, however, prolonged below-normal sea temperatures in the Northwest Atlantic Ocean contributed to changes in capelin behaviour and biology (Carscadden et al., 2001; Davoren et al., 2006). Capelin began to spawn later, in July and August (Carscadden et al., 2001). Although beach water temperatures during July and August are typically warm, occasionally exceeding the temperature range at which capelin can successfully spawn, capelin year-class abundance during these months was high in the 1990s and the frequency of good year-classes increased (Carscadden et al., 2001). In this case, demersal spawning may have been more important to capelin populations than previously reported. Demersal spawning temperatures are lower and more stable than those on the beach since they are less affected by solar and wind influences.

1.3.1. Capelin in the Northwest Atlantic Ocean

In the 1990s capelin stocks underwent major changes in distribution, timing of spawning and average body size of individual fish. These changes corresponded with changes in predation associated with the collapse of major ground-fish stocks and changes to the ocean climate (Carscadden et al., 2001; Carscadden et al., 1997; Davoren et al., 2006). Capelin are an important energy source; changes to their biology have affected aspects of the ecosystem of the Northwest Atlantic Ocean many of their predators in this region, most notably the Atlantic cod (*Gadus morhua* Linnaeus, 1758) (Davoren et al., 2006) and the diet and condition of seabird offspring (Davoren et al., 2006; Davoren and Montevecchi, 2003; Davoren and Montevecchi, 2005).

In 2000 a study was conducted on the impact of capelin spawning on the foraging strategies of large vertebrate predators in the area surrounding the Funk Island Reserve off northeast Newfoundland (Davoren et al., 2003b). This study and additional research carried out in the same region from 2001 to 2003 led to the discovery of demersal spawning within the 50 m depth contour (Davoren et al., 2006). As a result of these studies an NSERC Strategic Grant was awarded in 2003 to researchers at Memorial University of Newfoundland (MUN) and Northwest Atlantic Fisheries Centre (NAFC) of the Department of Fisheries and Oceans (DFO), in partnership with commercial fishers. The goal of the project is to gain a better understanding of the environmental conditions that influence capelin recruitment and ecology. Specifically, some of the key objectives of the study were:

- To examine 'hotspots' of intensive whale and seabird feeding and identify the biophysical factors that draw them to those locations

- To examine the role of capelin in marine food webs in the Northwest Atlantic Ocean
- To predict the impact of fishing and climate change on capelin and its ecosystem

This thesis, which forms one component of the NSERC Project, aims to use acoustic remote sensing tools and techniques to characterize, classify, and map capelin demersal spawning sites and to characterize them according to water temperature range, sediment size range, and bathymetric structure. This information will then be used as a template to identify other demersal spawning areas.

1.4. Study area

This study was conducted along the Straight Shore of northwest Newfoundland (Figure 1-8) where Davoren et al. (2003) discovered five demersal spawning sites, and where Penton (2006) discovered four additional sites (Figure 1-8). These sites lie 1.5 km to 11.5 km from the beach in circa 18 m water depth. Interestingly, the postglacial lowstand of sea-level in this area occurred as a depth of circa 17-18 m around 8600 (radiocarbon) years ago (Bell and Renouf, 2003; Shaw and Edwardson, 1994) (Figure 1-8) which coincides with the Carscadden et al. (1989) suggestion that demersal spawners were originally beach-spawners.

1.4.1. Straight Shore seabed geology

The seabed of the inner shelf from Cape Freels to Musgrave along the Straight Shore is underlain by Devonian granites, whereas Silurian-Devonian sedimentary rocks dominate the area off Fogo Island (Figure 1-8). Inshore (<75 m water depth) the seabed

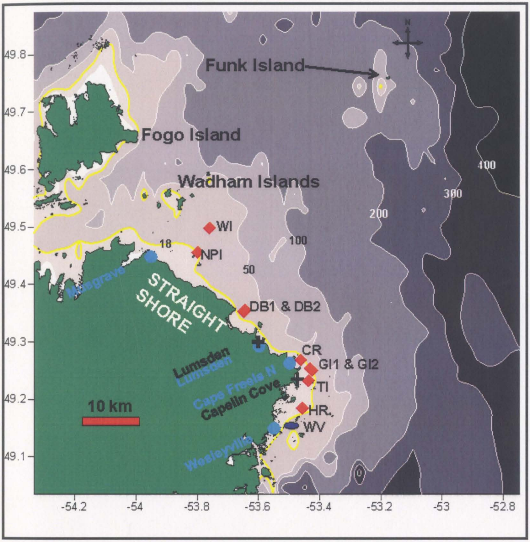

Figure 1-8: Map of the study area showing locations of places mentioned in the text. The demersal spawning sites are marked by red diamonds and the non-spawning site is marked by a blue oval. Each of the sites is labelled with their abbreviated code as follows: WI (Wadham Islands); NPI (North Penguin Island); DB1 & DB2 (Deadman's Bay 1 and 2); CR (Cracker's Rock); GI1 & GI2 (Gull Island 1 and 2); TI (Turr Island); HR (Hincks Rock); WV (Wesleyville). The two beach spawning sites are marked by black crosses, towns by cyan circles. Depth contours are marked at 100 m intervals except for the submerged postglacial sea-level lowstand at 18 m (yellow).

is more rugged and uneven, covered with coarse clastic sediments (Shaw et al., 1999). The sediment is dominated by gravel and some sand, probably the result of reworking by waves, tidal currents and icebergs (Shaw and Edwardson, 1994). Seabed ripples are 60-80% fine sand gravel. Samples from sandy areas were composed of medium to fine sand, containing pebbles, shell hash and sand dollars (*Echinarachnius parma*, Lamarck, 1816) (Shaw et al., 1999). The relief averages only a few meters. Bedrock veneered with boulders account for 5% of the seabed and are surrounded by gravel and sand deposits up to 9 m thick (Shaw et al., 1999). Gravel ripples were extensive in the area with an average wavelength of 2.3 m and orientation between 108° and 152°, running parallel to the shoreline (Shaw et al., 1999). The ripples tended to be found at depths of 29 m to 73 m. In places, sand sheets overlie gravel which are lined by sand dunes with an average wave length of 8 m (Shaw et al., 1999).

The offshore (>75 m) is more rugged than the inshore (Shaw et al., 1999). Bedrock outcrops cover 20% of the seabed but have fewer boulders than the inshore. The available sediments are furrowed and pitted by icebergs (Shaw et al., 1999). Bedrock forms 50-80% of the low relief seabed in the area between the Wadham Islands and Fogo Island, which is between 125 m and 150 m water depth. East of Fogo Island, the seabed consists mainly of well sorted medium sand and shell hash with some pebble-cobble gravel (Shaw et al., 1999).

1.4.2. Northwest Newfoundland oceanography

The oceanography of the northeast coast of Newfoundland is largely determined by the Labrador Current (Figure 1-9) (Colbourne et al., 1997a). The Labrador

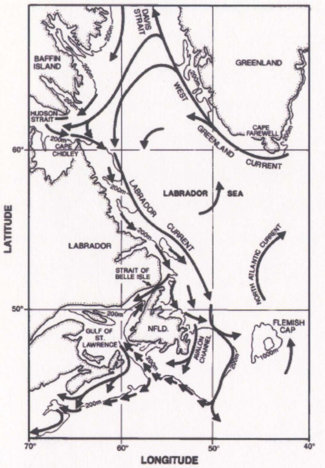

Figure 1-9: Map of the Northwest Atlantic showing the major current systems (Colbourne et al., 1997a).

Current transports cold relatively fresh polar water, along with sea ice and icebergs from the Arctic Ocean. The current is formed near Cape Chidley, Labrador, and is fed by Arctic waters from the eastern Arctic through Davis Strait and from Hudson's Bay and the Arctic Archipelago through Hudson Strait (Colbourne et al., 1997a).

The Cold Intermediate Layer (CIL) is a dominant feature of the ocean water temperature structure on the continental shelf for most of the year (Colbourne et al., 1997b). The CIL is a large body of subzero (Celsius) water that is bounded by a comparatively warm surface layer (>0°C) and warm continental slope water (>0°C). In winter, the thermal stratification of the water column breaks down. Cold winters with extensive ice cover increase the thickness of the CIL and reduce the thickness of the warm surface and bottom layers (Prinsenberg et al., 1997). In the winter, the inshore warm surface layer disappears, the water cools down to near the freezing point due to winter cooling and strong surface mixing from winter storms (Colbourne et al., 1997a). In the spring and summer, the water column re-stratifies due to ice melt and seasonal heating, causing the CIL to become trapped between the warm surface layer and the warm slope water near the bottom. In the summer the CIL stretches from the bottom of the seasonally-heated warm surface layer (30-50 m water depth) to the top of the warm bottom layer (>50 m water depth in the nearshore and >250 m water depth in the offshore, approximately 50 km from shore). The thickness of the CIL ultimately influences the depth of suitable capelin spawning temperatures inshore.

The seasonal cycle of salinity for the waters off the coast of northeast Newfoundland depends on local ice melt and the flux of freshwater from Baffin Bay and Hudson Bay (Prinsenberg et al., 1997).

1.5. Conceptual model and research questions

Throughout the Northern Hemisphere Circumpolar Region, capelin spawn at a wide variety of water depths (Table 1-1) and therefore water depth does not appear to be a factor that controls spawning. Water temperature, however, has been cited as a major control on the timing of spawning as well as egg survival and development (Carscadden and Frank, 2002; Carscadden et al., 2001; Carscadden et al., 1997; Davoren et al., 2006; Nakashima and Wheeler, 2002; Templeman, 1948). Capelin spawning occurs at temperatures as low as 0.1°C (Carscadden et al., 1989; Thors, 1981); however, egg development and larval emergence at these temperatures were negligible. Demersal spawning, egg development, and larval emergence has been most successful at water temperatures that are greater than or equal to 2°C (Carscadden et al., 1989) and less than or equal to 12.1°C (Nakashima and Wheeler, 2002). Therefore, successful capelin spawning is limited by water temperatures that are between 2°C and 12°C.

Although depth does not appear to limit demersal capelin spawning, it is closely linked to temperature as demonstrated by the seasonal variation of the thickness (depth limits) of the CIL and the warm surface and bottom layers of the water column of the Newfoundland Shelf. Prior to the 1990s capelin in Newfoundland spawned during a two to three week period in June (Davoren et al., 2006). In 2004 demersal spawning was observed at seven of the nine sites off the Straight Shore during July and August (Penton, 2006). Historical July water temperature data (1990 to 2000) from within the study area show that the warm surface layer (>0°C) was constrained to 0-50 m water depth (Davoren et al., 2006). It is therefore proposed that demersal spawning habitats in the study area are restricted to water depths of less than 50 m because of the summer water temperature constraint.

Substrate grain-size is also consistent for spawning habitats (0.5 mm to 15 mm; Table 1-1) and is thought to be a controlling factor in capelin spawning (Carscadden et al., 1989). Therefore, it is proposed that seabed substrate may also play an important role in habitat selection for spawning by capelin. It may be because eggs that are spawned demersally require some protection from currents; it is likely that the sandy gravel substrate will have some level of roughness (rugosity) and local relief.

The conceptual model for demersal capelin spawning in coastal northeast Newfoundland is that capelin spawn on substrate that ranges between 0.5 mm and 15 mm at bottom water temperatures that range between 2°C and 12°C. Given that the CIL tends to occur below 50 m water depth in the summer, demersal spawning should occur in the warm surface layer at < 50 m water depth, above the CIL.

To test this conceptual model the following research questions were addressed:

1. What are the physical factors that constitute demersal capelin spawning habitats at each of the study sites?
    a. What is the water temperature?
    b. What is the bathymetry?
    c. On what substrate sizes does spawning occur?
    d. How do the physical characteristics of demersal spawning sites off northeast Newfoundland compare with those elsewhere?
    e. Are there similarities between demersal and beach spawning habitats in northeast Newfoundland?
2. Can demersal spawning sites be delineated on the basis of their acoustic signatures?

Unsupervised Classification

a. What is the acoustic signature of spawning sites in the area?

b. Is there a characteristic acoustic signature for all spawning sites?

c. Is there a distinct difference in acoustic signature between spawning and non-spawning sites?

Supervised Classification

d. What is the size class of the spawning substrate that is associated with acoustic signatures?

e. Once identified, can the acoustic signatures be used to train the QTC IMPACT system to recognise similar signatures in future surveys?

f. What is the potential for mapping new spawning sites using the acoustic signatures identified in this study?

2. Materials and Methods

In this chapter the tools and techniques used to accomplish the research objectives are presented. The first part summarizes the approach used to select the study sites. This summary is followed by a justification of the survey design and methods at each of the study sites. The demersal spawning sites are classified using the supervised classification approach. Supervised classification requires ground-truth data to verify acoustic signatures, therefore substrate sampling methods and analysis are described. The unsupervised classification method differentiates between acoustic signatures of different seabed types. Unlike the supervised classification, the unsupervised method does not require ground-truth data. The purpose of the unsupervised classification is to isolate acoustic signatures of different seabed types, not to identify them. The final part of this chapter focuses on methods used to investigate the substrate morphology, roughness (rugosity) and water temperature of the spawning sites.

2.1. Site selection

Nine spawning sites were discovered by Davoren et al. (2003) and Penton (2006) between 2002 and 2004. When each spawning site was discovered, one bathymetric value of the site and its geographic coordinates (point location) were recorded (Davoren et al., 2006; Penton, 2006). The sites were named for their location relative to bays, offshore islands, or coastal towns found along the Straight Shore (Figure 1-8). In 2002 the Gull Island 1 (GI1) and Gull Island 2 (GI2) spawning sites were discovered using a Remotely Operated Vehicle (ROV) (Table 2-1) (Davoren et al., 2003a). The Wadham Islands (WI), Deadman's Bay 1 (DB1) and Deadman's Bay 2 (DB2) spawning sites were

Table 2-1: Number of ROV recordings and sites covered from 2002 to 2005.

Year	*Vessel*	*No. of Samples*	*Sites Sampled*
2002	CCGS *Shamook*	16	GI1 and GI2
2003	CCGS *Shamook and LEII*	51	GI1, GI2, DB1, DB2, WI
2004	*LEII*	32	GI1, GI2, DB1, DB2 NPI, TI, HR, CR
2005	CCGS *Shamook*	3	WI, NPI

Table 2-2: Total number of grab samples collected and sites covered from 2001 to 2005.

Year	*Vessel*	*No. of Samples*	*Sites Sampled*
2003	CCGS *Shamook and LEII*	278	WI, NPI. DB1, DB2, GI1, GI2, WV
2004	*LEII*	10	TI, GI1, GI2, HR, CR
2005	CCGS *Shamook*	78	WV, WI, TI, CR

Table 2-3: Acoustic seabed surveys of the study sites.

Date	*Vessel*	*Survey*	*Spawning Site*	*Area (km)*	*Sample Design*
15-Aug-03	*LEII*	GI	GI1, GI2	1.0 x 2.0 km	Grid
04-Dec-04	CCGS *Shamook*	WV	n/a	2.0 x 4.0 km	Grid
29-Jun-05	CCGS *Shamook*	HR	HR	3.0 x 3.0 km	Grid
29-Jun-05	CCGS *Shamook*	TI	TI	2.0 x 2.0 km	Star
30-Jun-05	CCGS *Shamook*	CR	CR	2.0 x 2.0 km	Star
02-Jul-05	CCGS *Shamook*	DB	DB1, DB2	2.0 x 2.0 km	Star
02-Jul-05	CCGS *Shamook*	NPI	NPI	2.0 x 2.0 km	Star
July 2-3, 2005	CCGS *Shamook*	WI	WI	3.7 x 7.5 km	Grid

discovered in 2003 (Davoren, 2004) and the North Penguin Island (NPI), Cracker's Rock (CR), Turr Island (TI) and Hincks Rock (HR) spawning sites were discovered in 2004 (Figure 1-8).

The Wesleyville (WV) survey was selected for analysis in this study as an area of non-spawning. Three "non-spawning" sites within the WV survey were analyzed to determine the physical and acoustical features that deter demersal spawning (Figure 1-8). A grab sampling program carried out at this site in 2003 revealed anoxic, fine-grained sediments and absence of capelin eggs (Table 2-2) (Davoren, 2004). Based on these observations, it was concluded that capelin likely do not spawn in this location.

Eight surveys were conducted to acoustically map the spawning and non-spawning sites (Table 2-3). Each survey was named for the local spawning site, and in two cases included two adjacent sites at Deadman's Bay (DB1 and DB2), and Gull Island (GI1 and GI2) (Table 2-3). The division of the Deadman's Bay and Gull Island spawning sites was set by the NSERC Project and was maintained for this study. The surveys were restricted to 18-50 m water depth. The Gull Island survey was conducted by MUN and NAFC scientists aboard the commercial fishing vessel *Lady Easton II* in 2003 (Davoren et al., 2006) and the Wesleyville (WV) acoustic survey was conducted aboard the Canadian Coast Guard Ship (CCGS) *Shamook* in 2004. The remaining six surveys were conducted in 2005 aboard CCGS *Shamook*.

2.1.1. Survey design

Prior to this study, information about each of the spawning and non-spawning sites was based on the point location of a single grab sample or on ROV observations. To determine the dimensions, substrate composition, and seabed morphology of each of the sites, acoustic surveys were conducted using two different sampling designs. A systematic grid sampling pattern was used for the Gull Island (GI), Hincks Rock (HR), Wadham Islands (WI) and Wesleyville (WV) surveys (Figure 2-1). A star sampling pattern was used at the Deadman's Bay, Cracker's Rock (CR), North Penguin Island (NPI) and Turr Island (TI) surveys (Figure 2-2). The grid survey pattern was employed at sites that were open and had few navigational obstacles such as shoals and islands. The star design was used to maximize sampling through the spawning sites that were less open and did not easily lend themselves to grid pattern surveying. The spawning site was the central point of the star and was sampled repeatedly, as each line of the survey passed through the star centre.

2.2. Ground-truth data and acoustic seabed classification

To classify the demersal spawning sites the supervised classification approach was used. This approach uses ground-truth data to verify acoustic signatures isolated by the unsupervised classification. The unsupervised classes were ground-truthed using a combination of grab samples and ROV images. Geographical coordinates were recorded for all acoustic and ground-truth data.

2.2.1. Ground-truth data collection and analysis

Sediment samples were collected using a standard 30 cm^2 Van Veen bottom grab sampler at the spawning sites. Samples were emptied into a 40 l container and a 250 ml representative sub-sample was collected in a 500 ml Mason jar and preserved with a 10% formalin-seawater solution (Davoren et al., 2006). In the laboratory the samples were

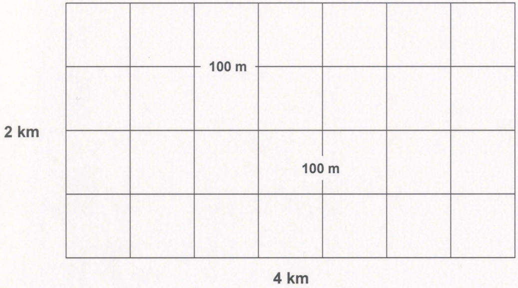

Figure 2-1: Grid survey sample design.

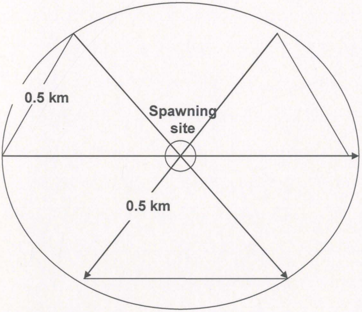

Figure 2-2: Star survey sample design.

poured onto a 0.15 mm sieve and flushed with water. Grain-size analysis of the sediment was performed according to the methods described in Folk (1980). Sediment samples were dried in a convection oven for 72 hours. Once dry, the samples were fractioned through a series of 12 sieves for 15 minutes on a Ro-Tap Shaker, using the Canadian Standard Sieve Series. Sieve sizes (mm) used were 31.5, 22.4, 16.0, 11.2, 8.0, 2.0, 1.0, 0.71, 0.50, 0.25, and 0.15. The sediment in each sieve was weighted to 0.01 g.

Statistical parameters of the sediment were calculated to determine the size range and degree of sorting of the particles found at each of the study sites. These statistical parameters gave some indication of the substrate composition at each of the sites and the manner in which it varied between sites.

Equations for calculating the statistical parameters of the sediment were based on methods outlined in Folk (1980) and Prothero and Schwab (1997) (Table 2-4). The mean, median, sorting, skewness and kurtosis were derived from cumulative percentage and cumulative probability percentage plots (Figure 2-3). The mode was determined from the highest peak of the percentage histogram (Figure 2-3). The equations and the cumulative percentage distribution of the samples were used to describe the sediment composition at each site. All equations were calculated using phi (Φ) unit values. The phi scale uses a logarithmic-based unit of measurement where grain-size diameter in phi is equal to the $-\log_2$ of grain-size diameter in millimetres (Prothero and Schwab, 1997).

The graphical median corresponds to the sediment diameter that is halfway between grains that are fine and those that are coarse according to the Wentworth scale

Table 2-4: Formulas for calculating grain-size statistics using phi (Φ) unit values probability plots (Prothero and Schwab, 1997)

CENTRAL TENDENCY	***Modal Class: most abundant class interval on histogram***	
	Graphic Mean (M_Z): $M_Z = (\Phi_{16} + \Phi_{50} + \Phi_{84})/3$	
	Median = 50Φ	
SORTING	***Inclusive graphic standard deviation (sorting): $\sigma_I = (\Phi_{84} - \Phi_{16})/4 + (\Phi_{95} - \Phi_5)/6.6$***	
	<0.35Φ	very well-sorted
	0.35Φ to 0.50Φ	well-sorted
	0.50Φ to 0.71Φ	moderately well-sorted
	0.71Φ to 1.00Φ	moderately-sorted
	1.00Φ to 2.00Φ	poorly-sorted
	>2.00Φ	very poorly-sorted
SKEWNESS (SYMMETRY)	***Inclusive graphic skewness: $Sk_I = (\Phi_{16} + \Phi_{84} - 2\Phi_{50})/(2(\Phi_{84} - \Phi_{16}) + (\Phi_5 + \Phi_{95} - 2\Phi_{50})/2(\Phi_{95} - \Phi_5)$***	
	>+0.30	strongly fine-skewed
	+0.30 to +0.10	fine-skewed
	+0.10 to -0.10	near-symmetrical
	-0.10 to -0.30	coarse skewed
	<-0.30	strongly coarse-skewed
KURTOSIS	***Kurtosis: $K_G = (\Phi_{90} - \Phi_5)/2.44(\Phi_{75} - \Phi_{25})$***	
	>1.0	excessively peaked (leptokurtic)
	1.0	normally peaked (mesokurtic)
	<1.0	deficiently peaked (platykurtic)

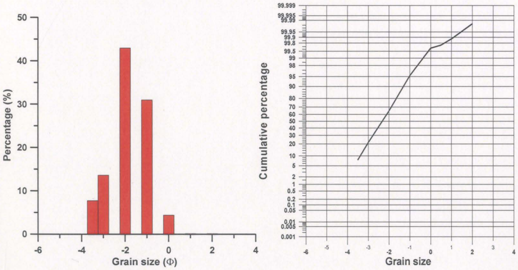

Figure 2-3: Histogram and Cumulative Probability Curve plots used to calculate statistical measures.

(Folk, 1980; Freitas et al., 2003a; Prothero and Schwab, 1997; Wentworth, 1922) (Figure 2-3). The inclusive graphic standard deviation was calculated to determine the degree of uniformity or homogeneity of the sediment (Table 2-4). It includes 90% of the distribution and is a better measure of sorting than the graphic standard deviation which accounts for only the central two-thirds of the curve. The inclusive graphic skewness was calculated to identify the predominance of particular sediment fractions (Table 2-4). It accounts for 90% of the curve whereas the graphic skewness covers only the central 68% of the curve. Kurtosis was calculated to assess the percent frequency distribution of the particle sizes. Distributions that were excessively peaked (leptokurtic) had a smaller range in particle size than a sample that was less peaked (platykurtic) (Table 2-4). Mesokurtic samples were normally distributed (Table 2-4). Based on these analyses, the middle 90% of the cumulative distribution curve was used to determine the sediment size range for all sediment samples taken from the spawning sites.

Additional ground-truth data were obtained using an ROV equipped with an underwater video camera (VideoRay PRO; Video Ray LLC, Phoenixville, Pennsylvania, USA) for areas that were difficult to sample using the bottom grab, such as bedrock, boulders and areas covered in macroalgae. The ROV was first used in 2002 by Davoren et al. (2006) from the *Lady Easton II* to observe anti-predator behaviour of capelin shoals. Two demersal spawning sites were discovered incidentally. In 2003 and 2004 additional videos of demersal capelin spawning were recorded. As part of this study, in 2005 detailed recordings were made of substrate surrounding known demersal capelin spawning sites where grab sampling was limited by the substrate. A Global Positioning System (GPS) was used to record geographic coordinates and time stamps when the ROV was deployed.

In addition to the grab samples, the 2005 ROV images were used to develop the training dataset for the supervised classification. Video clips and still images of desired features from the digital video recordings were extracted using the Pinnacle Studio (v.9.0) image software (Avid Technology Inc., Mountain View California, USA). The position of each extracted ROV images was overlaid with the acoustic track of the unsupervised classification data. The ROV images were used to describe the North Penguin Island (NPI) site, which was difficult to sample with the grab sampler.

In 2004, as part of the NSERC Project, a study was conducted on beach spawning at two beaches on the Straight Shore (Andrews, 2005). Sediment samples from that study were used in the present study to compare beach and demersal substrates.

2.2.2. Acoustic data collection and analysis

The acoustic surveys were conducted using a normal incidence BioSonics DT-X 120 kHz dual beam system (BioSonics DT-X, BioSonics Inc., Seattle Washington). The seabed was ensonified at a ping rate of 1 ping per second and 0.4 ms pulse width. The transducer was housed in a hydrodynamic V-fin that was towed at speeds of 5-6 knots (2.6-3.1 ms^{-1}) positioned and approximately 5 m below the surface off the starboard side of the ship. The raw, unprocessed acoustic data collected from the demersal spawning sites with the BioSonics DT-X were classified using the QTC IMPACT system.

2.2.2.1. Unsupervised classification

The acoustic data were first analyzed using unsupervised classification in QTC IMPACT. In this method, raw acoustic echoes are collected with corresponding positional data and processed through QTC IMPACT to determine the acoustic variability of the surveyed seabed (Freitas et al., 2001). To reduce the signal-to-noise ratio, the echoes were analyzed in groups of five. The depth of the seabed was established using the QTC IMPACT bottom pick algorithm. QTC IMPACT uses the first return signal in the echo from the seabed (Figure 2-4) and applies a series of algorithms to digitize and analyze the shape of the echo (Wienberg and Bartholoma, 2005). The algorithms generate 166 variables which characterize each echo (Collins, 1999; Collins et al., 1996; Collins and Lacroix, 1997; Preston and Collins, 2000). Using Principle Components Analysis (PCA), the 166 variables are reduced to optimal variables that can discriminate the seabed types. These variables are compressed to three composite variables with numeric values which are denoted as Q1, Q2, and Q3 (Q-values) (Collins, 1999). Within QTC IMPACT, each echo is clustered according to its Q-values. Therefore, when the three Q-values of several echoes from a single seabed type are plotted against each other, they form a single cluster or class. Similarly, when the Q-values of echoes from three different seabed types are plotted against each other, they will form three distinct clusters (Collins, 1999).

Clustering in QTC IMPACT is based on a progressive splitting process (Freitas et al., 2003a). At the start of the clustering process, before splitting, one class is displayed in a three dimensional space referred to as Q-space (where the three Q-values form x, y, and z axes) and is represented by a cluster or ellipsoid (class = n (splits) + 1). The ellipsoid is continually split as long as the total score of the clusters continues to decrease. The total score is the sum of the data points multiplied by the Chi^2 values.

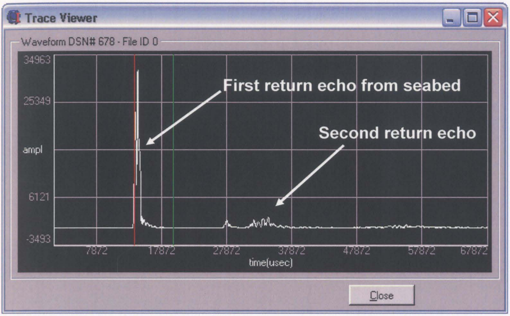

Figure 2-4: Echo trace showing the first and second echoes on a time vs. amplitude plot for a single ping generated by the BioSonics DT-X 120 kHz transducer.

Chi^2 is a measure of the clumpiness of each cluster in Q-space (Quester Tangent Corporation, 2004). The ellipsoid has three principle axes: primary, secondary, and tertiary (Figure 2-5). The primary axis is the longest line connecting the centre of the ellipsoid (centroid) and the point on the surface. This axis indicates the direction of greatest variability. The secondary axis is the second longest line connecting the centre of the centroid and the furthest point on the surface of the ellipsoid when perpendicular to the primary axis. The tertiary axis is perpendicular to both the primary and the secondary axes while passing through the centroid. Splitting is done manually, based on the total score and amount of change in the total score is performed on each axis of each class, but only proceeds on the axis of the class that produces the lowest total score. Further splits lead to smaller changes in the total score. When the number of splits is plotted against the total score, the inflection point of the resulting curve gives a good indication of the optimal split level (Freitas et al., 2003a; Quester Tangent Corporation, 2004). Echoes with similar characteristics form clusters that define the acoustic classes (Hutin et al., 2005; Quester Tangent Corporation, 2004) that were mapped for each acoustically surveyed site. The optimal split level was determined by plotting the total score against the split level to find the inflection point or the point beyond which the total score decreases little (Figure 2-6).

Each of the acoustic surveys was processed separately and the resulting unsupervised classifications are site-specific.

2.2.2.2. Supervised classification

A training dataset or catalogue must be developed to classify the seabed with the supervised approach. The training dataset is achieved by determining the seabed

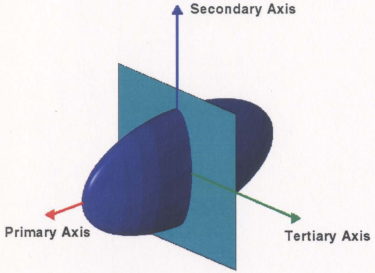

Figure 2-5: Location of the primary, secondary and tertiary axis where the ellipse (cluster) can be split (Quester Tangent Corporation, 2004).

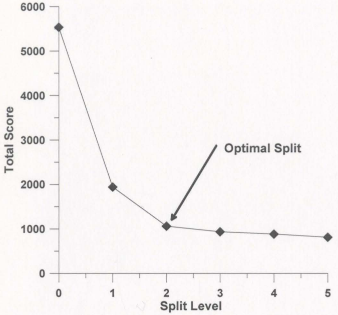

Figure 2-6: Example of a total score vs. split level based on manual splitting to determine the optimal split level where there is a inflection point in the curve beyond which total score decreases little.

characteristics of acoustic signals. Unsupervised classification and ground-truthing are, therefore, both carried out as part of the supervised classification.

Four seabed types were identified from the grab samples and the ROV images. The unsupervised classification data for each of the surveys were imported into the mapping software Surfer 8.0 (Surfer Mapping System, Golden Software, Inc., Golden Colorado, USA) to produce acoustic seabed maps (Freitas et al., 2003a) and the positions of the grabs and ROV images were overlaid onto the maps (Figure 2-7).

For the first seabed type that was identified, three to five survey lines were isolated; and these were represented by one unsupervised acoustic class and bisected the point position of either a grab sample or an ROV image of that seabed type. The process was repeated for the other three seabed types. A series of 50 contiguous data points was selected from each of the isolated survey lines. Only 50 data points were chosen because they formed the most tightly-packed clusters. Combinations of the dataset (with 50 points representing each of the four seabed types) were tested to form the training dataset. All combinations of the four decimated survey lines (50 data points each) formed four distinct clusters when reduced to the Q-values. The selected training dataset was the combination that formed the four most tightly-packed clusters most widely separated in Q-space (Figure 2-8).

The training dataset was made up of survey lines from four different acoustic surveys within the study. The acoustic surveys from each of the sites were classified according to the training dataset. All acoustic signals from each of the surveys were then classified as one of four seabed types. This method enabled a comparison of the surveys according to the variation and spatial extent of each of the classes or seabed types.

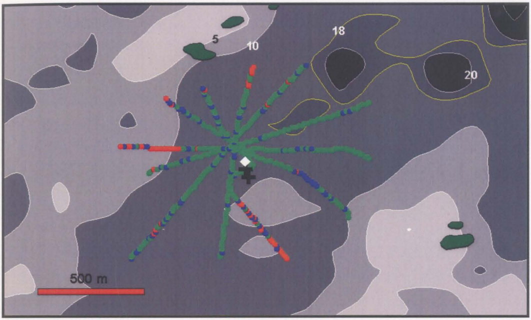

Figure 2-7: Grab samples (black crosses) and spawning site position (white diamond) overlaid onto unsupervised classification acoustic survey.

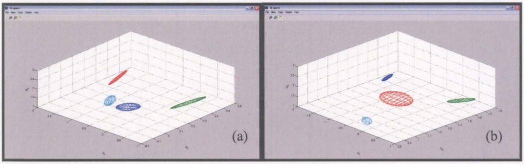

Figure 2-8: Two combinations of the four supervised classes in Q-space. In (a) two of the classes are closely spaced while the other two are separated. In (b) the four classes are widely separated.

2.3. Demersal spawning habitat characteristics

The following section details the analysis that was carried out to determine the physical and environmental characteristics of the demersal capelin spawning habitat.

2.3.1. Demersal spawning site dimensions and scale

To estimate the areal dimensions of the spawning sites, the point locations of each of the nine spawning sites were plotted in Global Mapper (Global Mapper Software LLC, Olathe, Kansas, USA) to determine the coordinates for a 1.0 km^2 box (the area initially assumed to cover the sites) surrounding each of the sites. In the case of the non-spawning site three 1.0 km^2 boxes were created that centered on grab sampling sites across the east-west dimension of the acoustic survey. These coordinates were entered in the statistical software package SAS (Statistical Analysis System, SAS Institute Inc., Cary, North Carolina) (SAS, 2000) to determine the percent coverage, mean depth, and relief of each of the unsupervised and supervised classes in each of the 1.0 km^2 survey areas. Relief was calculated in SAS and was the difference in depth between data points over the distance between data points. The analysis was re-run for 0.05 km^2, 0.5 km^2, 1.0 km^2, 1.5 km^2 and 2.0 km^2 area to determine the change in percent coverage of the supervised classes with changes in spatial scale.

2.3.2. Seabed morphology

The depth and the relief of the supervised classes were analyzed to further describe the seabed morphology at each of the spawning sites.

Bottom depth data were generated from the QTC IMPACT bottom pick algorithm (Anderson et al., 2005; Quester Tangent Corporation, 2004). Analysis of depth was conducted in SAS. Comparisons between mean depth of the supervised classes were made graphically and statistically using the General Linear Model (GLM), Duncan's Multiple Range test, and the Student Maximum Modulus (GT2) test (SAS, 2000).

Relief of each of the supervised classes was calculated and defined as the change in depth (m) between adjacent observations along transects standardized to 1 km horizontal distance (m/km) (Anderson et al., 2005). The individual scores for the relief of the supervised classes were ranked with the Wilcoxon test. The Kruskal-Wallis test was used to evaluate the difference in relief between the four supervised classes. These tests were used because the relief data were not normally distributed.

2.3.3. Temperature

In 2004, thermisters were deployed at each of the point locations of the capelin spawning sites to record temperature at the seabed during spawning events (Penton, 2006). Spawning occurred at all but the Deadman's Bay sites that year. Due to technical difficulties, the temperature data for the North Penguin Island (NPI) site was lost. The mean temperature and the 95% confidence interval (CI) for the remaining data were calculated in SAS and then plotted in Grapher 5.0 (Grapher, Golden Software, Inc., Golden Colorado, USA). The spawning site temperature data were compared to the historical trends from Station 27. Station 27, established in 1946, is a standard hydrographic monitoring station located 8 km off St. John's Harbour in the inshore branch of the Labrador Current (Colbourne et al., 1997a). Temperature trends for June, July, and August, the months that capelin have been observed spawning in Newfoundland, were determined for 1960-2005 from Station 27 water temperature records.

3. Results

The first goal of this chapter is to illustrate the results of the acoustic seabed classification of the demersal spawning sites and the non-spawning site. The second goal is to characterize the environment that constitutes the demersal capelin spawning sites through analysis of the temperature of the water column and the seabed morphology.

The first result presented is the analysis of the ground-truth data from the grab samples and ROV images taken from the survey sites. This analysis is followed by the results of the unsupervised classification. These results are used to create the training dataset. They are followed by the presentation of the supervised classification of the seabed at each of the survey sites.

The thermal and morphological characteristics of the spawning sites are presented in the second half of this chapter. These data were used to determine the depth range of the lower and upper temperature boundaries for demersal capelin spawning off the northeast coast of Newfoundland. The correlation between temperature and depth was plotted for the sites where spawning occurred in 2004.

3.1. Acoustic classification

Eight acoustic surveys were carried out between 2003 and 2005 (Table 2-3). They encompassed the point location of the nine known spawning sites and an area where spawning does not occur. The sites were ground-truthed with grab samples and ROV images.

3.1.1. Substrate analysis

Grab samples collected at the spawning sites contained sediment with attached capelin eggs (Davoren et al., 2006). The substrate at the spawning sites and the non-spawning site ranged between fine sand and coarse pebble, approximately 0.125 mm to 32 mm in size (Appendix 1 to 9). In 2004, substrate samples were collected at two capelin spawning beaches along the Straight Shore. At Capelin Cove and Lumsden Beach (Figure 1-8), the substrate grain-size ranged from medium sand to coarse pebble, approximately 0.4 mm to 30 mm (Appendix 10 to 11).

Cracker's Rock (CR)

Two sediment samples were collected at the Cracker's Rock (CR) site. Both samples consisted of moderately-sorted granule pebble gravel that ranged in size from 1.4 mm to 13 mm (Appendix 1).

Deadman's Bay (DB)

Overall the substrate at the two Deadman's Bay sites (DB1 and DB2) was poorly-sorted with grain-sizes that ranged from medium sand to coarse pebble (Appendix 2 and 3). Four of the five samples from DB1 were dominated by pebble and granule gravel with very coarse sand; the other sample was coarse to very coarse sand with traces of granules and pebbles (Appendix 2). Three of the samples collected at the DB2 site consisted of poorly-sorted sediment that ranged from medium pebble down to coarse sand (Appendix 3). One sample was moderately-sorted, consisting only of pebbles and granule gravel.

Gull Island (GI)

The substrate at the Gull Island sites (GI1 and GI2) was generally finer than that at the other spawning sites. Eight samples were taken at the GI1 site (Appendix 4). Three samples had a very narrow size range of sediment consisting of medium to coarse sand (0.35 mm to 1.00 mm). Four other samples consisted of medium to coarse sand with minor pebbles. One sample was very poorly-sorted with a large range of substrate from coarse sand through to medium pebbles (0.31 mm to 22.5 mm).

Nine samples were taken from the GI2 site (Appendix 5). All but one of the samples was well-sorted. Sample number five was poorly-sorted and consisted of medium pebbles and granule gravel with traces of very coarse sand. Sample number seven was very well-sorted, consisting of medium pebbles with very coarse sand. Samples eight and nine both consisted of pebble and granule gravel. Sample two had the narrowest and smallest substrate size range, consisting of fine to medium sand, 0.35 mm to 0.51 mm. The remaining samples were predominantly sand with minor granules.

Hincks Rock (HR)

Two samples were taken at the Hincks Rock (HR) site (Appendix 6). Both were moderately well-sorted, consisting of granule gravel with very coarse sand.

North Penguin Island (NPI)

Grabs attempted at the North Penguin Island (NPI) site were unsuccessful; therefore, the ROV was used to identify the substrate at this site. There were patches of small gravel substrate which graded into larger substrate. There were also areas of large boulders with accumulations of finer gravel in between (Figure 3-1).

Figure 3-1: ROV image from the North Penguin Island (NPI) spawning site showing accumulations of gravel between boulders.

Turr Island (TI)

The samples from the Turr Island (TI) site consisted of a wide range of sediments from coarse sand to medium pebbles (Appendix 7).

Wadham Islands (WI)

Most of the samples collected from the Wadham Island (WI) spawning site were well-sorted and consisted of medium to coarse sand (Appendix 8).

Wesleyville (WV)

All eleven samples collected from Wesleyville (WV), the non-spawning site, consisted mainly of fine sand (Appendix 9).

Capelin Cove Beach (CC)

The samples collected at the Capelin Cove (CC) beach spawning site consisted of a wide range of sediments. Half the samples were well-sorted while the other half was poorly-sorted. All the samples consisted of coarse sand to pebbles-sized grains (Appendix 10).

Lumsden Beach (LD)

Most of the samples collected from the Lumsden (LD) beach spawning site were poorly-sorted. The sediment size range at this site was narrower than that at the Capelin Cove beach spawning site and the substrate contained more gravel than sand (Appendix 11).

Other Substrates

Additional grab samples and ROV images were taken at random throughout the acoustically surveyed areas. Macroalgae (*Laminaria* sp. and *Agarum cribrosum*) were found within the surveyed area of the North Penguin Island (NPI), Turr Island (TI) and Cracker's Rock (CR) surveys. Bedrock, cobble, and large pebbles were present throughout the Wadham Island (WI) site.

3.1.2. Unsupervised classification

Unsupervised classification was performed on each of the acoustic surveys. The acoustic data from each survey site was submitted to K-means clustering which was based on the progressive splitting process using the QTC IMPACT v3.4 post-processing software (Hutin et al., 2005). The decision to split clusters was based on the total score of the cluster (Appendix 12-19).

The inflection point was used to determine the optimal split level for the Cracker's Rock (CR), Gull Island (GI), and Hincks Rock (HR) surveys (Figure 3-2). The inflection point was reached after the second split level, which generated three unsupervised acoustic classes. Three classes were also generated for the Deadman's Bay

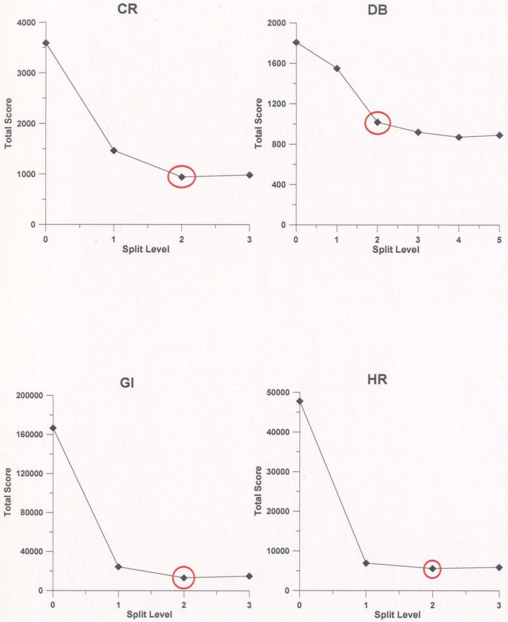

Figure 3-2: Plot of total score vs. split level to determine the optimal spilt level (red circle) for each survey.

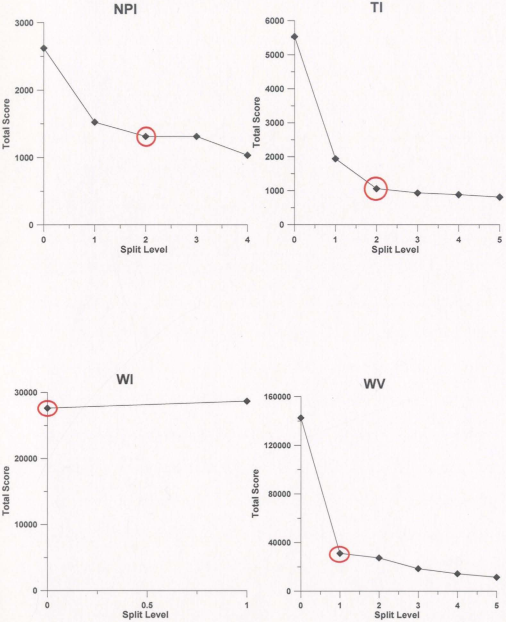

Figure 3-2: Continued.

(DB), North Penguin Island (NPI), and Turr Island (TI) sites where the optimal split level was determined to be the second split because the total score decreased only minimally with subsequent splits (Figure 3-2). The Wadham Islands (WI) survey generated only one class because the total score increased after splitting (Table 3-1, Figure 3-2). Two classes were generated at the non-spawning site survey because the total score decrease minimally after the first split (Figure 3-2).

The third class generated at the Deadman's Bay sites (DB1 and DB2), the Gull Island sites (GI1, GI2) and the Hincks Rock site (HR) had the highest spatial occurrence (Table 3-1). The third class accounted for 54.9% of the 1.0 km^2 area of the DB1 site, 58.8% of the DB2 site, 41.2% of the GI1 site, 42.4% of the GI2 site, and 58.4% of the HR site (Table 3-1). The second class was the most dominant class at the Cracker's Rock (CR), North Penguin Island (NPI) and Turr Island (TI) sites, covering 53.2% of the 1.0 km^2 area of the CR site, 54.9% of the NPI site, and 83.3% of the TI site (Table 3-1). When the splitting process was applied at the Wadham Islands (WI) survey site, the total score increased, indicating that this area was dominated by one class that covered 100% of the 1.0 km^2 survey area (Table 3-1). Of the two classes that were generated at the Wesleyville (WV1, WV2, WV3) sites, the second class was the most dominant, representing 79.5% of the WV1 1.0 km^2 survey area, 77.6% of WV2, and 93.6% of WV3 (Table 3-1).

For the Gull Island sites (GI1 and GI2), Hincks Rock site (HR), Turr Island site (TI) and the Wesleyville sites (WV1, WV2, and WV3), there was a statistically significant difference between the mean depths of each of the classes (Table 3-2). For the Cracker's Rock site (CR) the mean depth of Class 2 was 13.2 m and was statistically

Table 3-1: The percent coverage of the unsupervised classes over the 1.0 km^2 survey area surrounding the nine spawning sites and the three points of the non-spawning sites.

Survey	Class 1 (%)	Class 2 (%)	Class 3 (%)	Number of Classes
CR	7.0	53.2	39.8	3
DB1	7.6	37.6	54.9	3
DB2	5.6	35.6	58.8	3
GI1	31.0	27.8	41.2	3
GI2	33.8	23.9	42.4	3
HR	8.3	33.3	58.4	3
NPI	13.4	83.3	3.4	3
TI	10.4	72.1	17.5	3
WI	100.0	-	-	1
WV1	20.6	79.5	-	2
WV2	22.4	77.6	-	2
WV3	6.4	93.6	-	2

Table 3-2: Pearson correlation coefficient between depths and the three Q-values from QTC IMPACT.

Site	Q1	p-value	Q2	p-value	Q3	p-value
All sites	0.64190	<0.0001	-0.19072	<0.0001	-0.07979	<0.0001
CR	0.69925	<0.0001	0.10788	0.0098	0.21724	<0.0001
DB1	0.17620	<0.0001	0.02137	0.6236	-0.21333	<0.0001
DB2	0.04853	0.2629	0.00972	0.8227	0.09075	0.0360
GI1	0.62160	<0.0001	0.31822	<0.0001	0.20631	<0.0001
GI2	0.67280	<0.0001	0.19745	<0.0001	0.22631	<0.0001
HR	0.79485	<0.0001	0.15318	0.0003	-0.17847	<0.0001
NPI	0.47652	<0.0001	0.13947	0.0007	0.36698	<0.0001
TI	0.82355	<0.0001	-0.06045	0.1691	0.16987	0.0001
WI	0.13537	0.0131	0.00665	0.9059	-0.11025	0.0437
WV1	0.57532	<0.0001	0.08381	0.0011	-0.06823	0.0079
WV2	0.61795	<0.0001	0.07049	0.0132	0.15273	<0.0001
WV3	0.62854	<0.0001	0.43824	<0.0001	-0.45185	<0.0001

Table 3-3: Differences in mean depth of the unsupervised classes at each of the nine spawning sites over the 1.0 km^2 acoustically surveyed area using the GLM with the Duncan and GT2 tests. Means with the same letter are not significantly different.

	Mean Depth (m)						Degrees of Freedom			
Site	Class 1	Duncan/GT2 Grouping	Class 2	Duncan/GT2 Grouping	Class 3	Duncan/GT2 Grouping	Model	Error	F-value	p-value
CR	-18.0	B	-13.2	A	-17.7	B	2	570	147.13	<0.0001
DB1	-24.9	A	-26.1	B	-26.1	B	2	527	9.93	<0.0001
DB2	-26.9	A	-27.3	A	-27.3	A	2	531	1.22	0.2959
GI1	-25.9	A	-21.8	B	-18.7	C	2	7757	1357.50	<0.0001
GI2	-25.3	A	-20.8	B	-17.9	C	2	4017	1178.56	<0.0001
HR	-17.3	A	-13.4	B	-18.6	C	2	538	193.23	<0.0001
NPI	-17.2	A	-22.3	B	-21.6	B	2	588	79.19	<0.0001
TI	-7.2	A	-12.5	B	-10.3	C	2	516	204.73	<0.0001
WI	-29.2	-	-	-	-	-	-	-	-	-
WV1	-18.9	A	-21.0	B	-	-	1	1511	302.98	<0.0001
WV2	-20.9	A	-24.3	B	-	-	1	1233	281.72	<0.0001
WV3	-24.3	A	-30.6	B	-	-	1	1402	191.27	<0.0001

different ($F_{[2, 570]} = 147.13, p < 0.001$) from Class 3 (17.7 m) and Class 1 (18.1 m) (Table 3-2); Class 1 and 3 were not statistically different from each other (Table 3-2). For the Deadman's Bay 1 (DB1) site, the mean depth of Class 1 was 24.9 m which was statistically different ($F_{[2, 527]} = 9.93, p < 0.001$) from Class 2 (26.1 m) and class three (26.1 m); Class 2 and 3 were not significantly different from each other (Table 3-2). Similarly, with the North Penguin Island site (NPI), the mean depth of Class 1 was 17.2 m which was statistically different ($F_{[2, 588]} = 79.19, p < 0.001$) from Class 2 (21.7 m) and Class 3 (22.3 m); Class 2 and 3 were statistically similar (Table 3-2). For the Deadman's Bay 2 (DB2) site the mean depth of Class 1, 2, and 3 were 26.93 m, 27.3 m and 27.3 m respectively, which were not statistically different ($F_{[2, 531]} = 1.22, p < 0.2959$). The Wadham Islands (WI) site only had one unsupervised class with a mean depth of 29.2 m. The overall depth distributions of the unsupervised classes through the acoustic surveys of each of the spawning sites and the non-spawning site are displayed in Figure 3-3 through to Figure 3-10. Depths at the DB and WI sites display little variability; at these sites there was no statistically significant difference in the depth of the unsupervised classes (Figure 3-3 and 3-9). The depth at the other sites varied throughout the area covered by the survey and at these sites the depths of the unsupervised classes were statistically different (Figure 3-3, 3-5 to 3-8 and 3-10).

3.1.3. Supervised classification

Supervised classification was performed on the eight acoustic surveys. This was accomplished by applying the training dataset, also known as the supervised catalogue, to all acoustic data from each of the eight surveys (Figure 3-11).

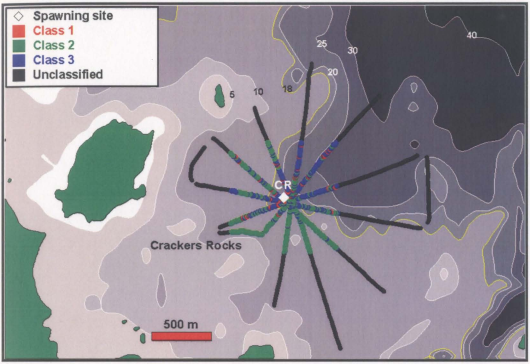

Figure 3-3: Unsupervised classification of the 1.0 km^2 acoustic survey from the Cracker's Rock (CR) spawning site.

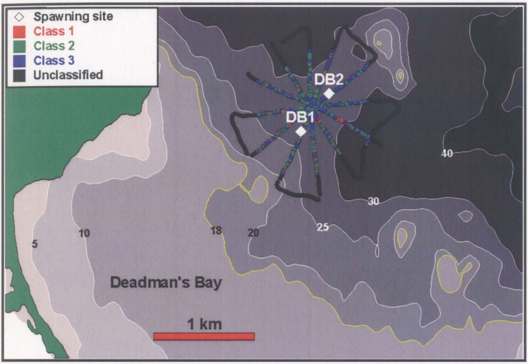

Figure 3-4: Unsupervised classification of the 1.0 km^2 acoustic survey from the Deadman's Bay (DB1 and DB2) spawning sites.

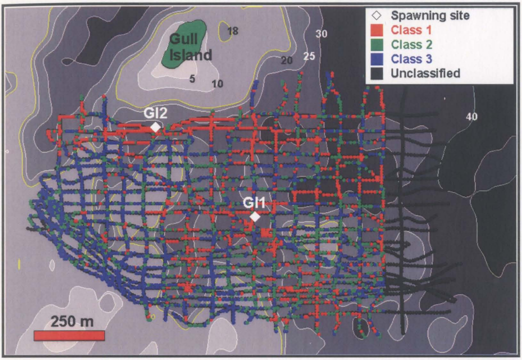

Figure 3-5: Unsupervised classification of the 1.0 km^2 acoustic survey from the Gull Island (GI1 and GI2) spawning sites.

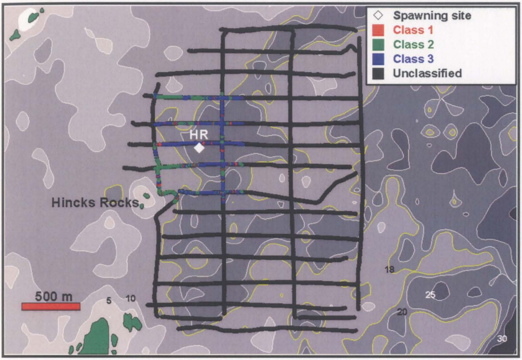

Figure 3-6: Unsupervised classification of the 1.0 km^2 acoustic survey from the Hincks Rocks (HR) spawning site.

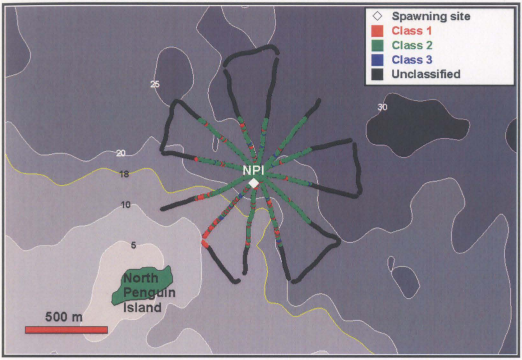

Figure 3-7: Unsupervised classification of the 1.0 km^2 acoustic survey from the North Penguin Island (NPI) spawning site.

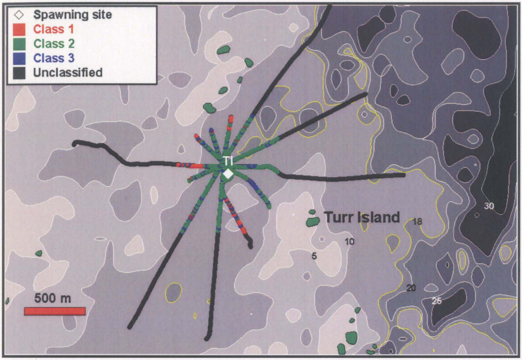

Figure 3-8: Unsupervised classification of the 1.0 km^2 acoustic survey from the Turr Island (TI) spawning site.

Figure 3-9: Unsupervised classification of the 1.0 km^2 acoustic survey from the Wadham Islands (WI) spawning site.

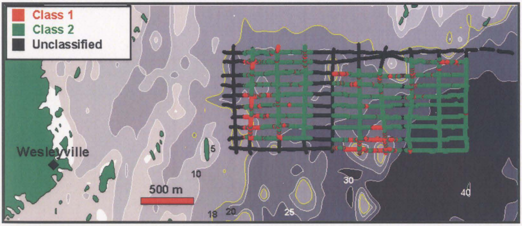

Figure 3-10: Unsupervised classification of the 1.0 km^2 acoustic survey from the Wesleyville (WV) non-spawning site.

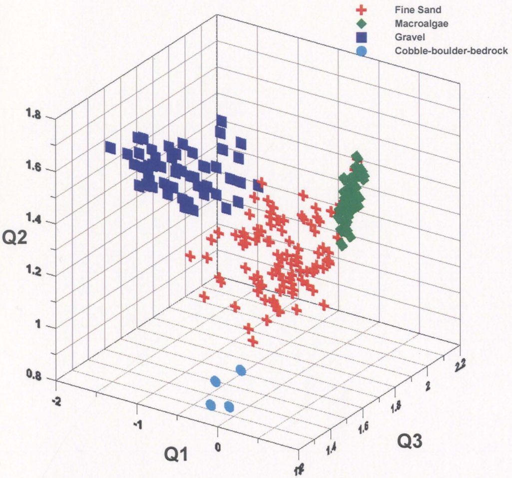

Figure 3-11: Three dimensional scatter plot of the supervised classes. Q1, Q2 and Q3 are the three most significant eigen values determined from Principle Components Analysis (PCA).

3.1.3.1. Acoustic training dataset

The results of the substrate analysis and unsupervised classification were used to create an acoustic supervised catalogue which is a training dataset containing acoustic files that are geographically associated with known seabed types. Grab samples and ROV images supply supporting evidence. Four seabed types were identified from the grab samples and ROV images encompassing fine sand, gravel (the spawning substrate), cobble-boulder-bedrock and macroalgae. The fine sand substrate was found most abundantly in the Wesleyville (WV) (non-spawning site). The geographic positions of the grab samples from the WV site were overlaid onto the unsupervised classification of the acoustic survey conducted at that site. The acoustic signature, which occurred within the same geographic space as the grabs samples, that represented the fine sand substrate was isolated within the acoustic files (survey track lines) of a single unsupervised class. The gravel substrate acoustic signature was isolated within the Turr Island (TI) survey and matched with grab samples from that spawning site. The cobble-boulder-bedrock acoustic signature was isolated within the Wadham Islands (WI) survey and matched with ROV images from the site (Figure 3-12). Finally the acoustic signature of the macroalgae was taken from the North Penguin Island (NPI) site and matched to ROV images from that site (Figure 3-13).

3.1.3.2. Spawning site dimensions and scale

For each of the nine spawning sites the percent occurrence of the four supervised acoustic classes was estimated at spatial scales 0.05 km^2 (the area of the point location of the spawning site), 0.5, 1.0, 1.5 and 2.0 km^2 around the point location of the spawning

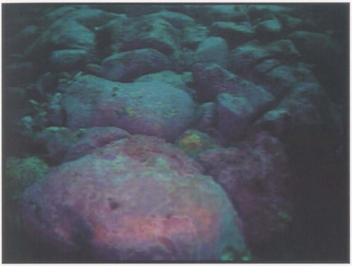

Figure 3-12: ROV Image of a cobble-boulder field from the WI survey site.

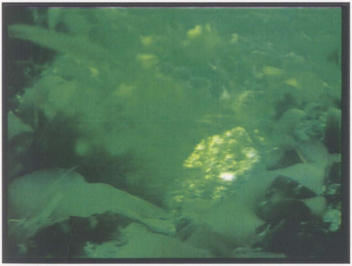

Figure 3-13: ROV images of macroalgae from the NPI survey site.

sites. At the 0.05 km^2 spatial scale, the acoustics detected the gravel substrate at three of the nine spawning sites. Gravel was not present at any of the Wesleyville (WV) non-spawning sites (WV1, WV2, and WV3). Gravel was detected at all of the spawning sites at the 0.5 km^2 scale. The occurrence of gravel decreased by 25% to 70% at the Cracker's Rock (CR), North Penguin Island (NPI) and Turr Island (TI) sites whereas at the non-spawning sites the occurrence of gravel increased by as much as 15%. Between 0.5 km^2 and 1.0 km^2, the percent coverage of gravel increased at the Deadman's Bay sites (DB1 and DB2); Gull Island 2 (GI2), Hincks Rock (HR), North Penguin Island (NPI), Wadham Islands (WI); and the Wesleyville 1 and 3 (WV1 and WV3) sites. It decreased at the Cracker's Rock (CR), Gull Island 1 (GI1), Turr Island (TI) and Wesleyville 2 (WV2) sites. Overall, the occurrence of gravel stabilized at the 1.0 km^2 scale. The mean percent coverage of gravel from 1.0 km^2 to 2.0 km^2 was approximately 32% (Figure 3-14; Table 3-6 to 3-8).

At the 0.05 km^2 scale, gravel (spawning substrate) covered 100% of the area for the CR, NPI, and TI sites (Table 3-4). At the same scale, fine sand covered 100% of the WV1 and WV3 sites (Table 3-4). At the GI1 site, fine sand accounted for 83.3% of the area while cobble-boulder-bedrock accounted for the remaining 16.7% (Table 3-4). At this scale, none of the supervised classes were acoustically detected at the DB1, DB2, GI2, HR, WI or WV2 sites (Table 3-4).

At 0.5 km^2, gravel accounted for 19.3% to 75.1% of the survey area (Table 3-5). The range decreased to 24.5% to 61.3% at 1.0 km^2 (Table 3-6). The occurrence of gravel at 1.5 km^2 and 2.0 km^2 was similar to the 1.0 km^2 scale (Table 3-7 and 3-8). The sites with the greatest occurrence of gravel were CR, GI1 and GI2 and TI; these sites were

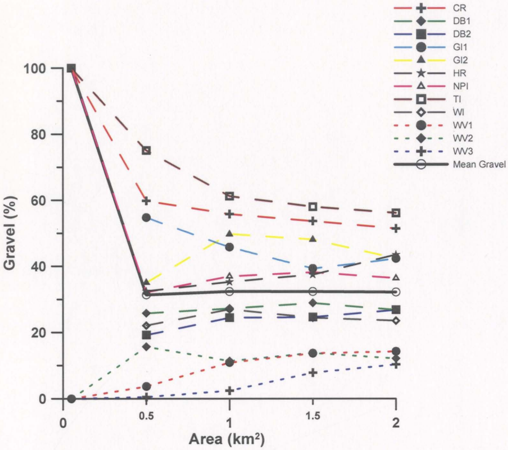

Figure 3-14: Mean percent coverage of gravel (spawning substrate) at 0.05, 0.5, 1.0, 1.5 and 2.0 km^2.

Table 3-4: Percentage of each supervised class by area for 0.05 km^2 area.

Survey	Fine sand	Macroalgae	Gravel	Cobble-boulder-bedrock
CR	0.0	0.0	100.0	0.0
DB1	n/a	n/a	n/a	n/a
DB2	0.0	0.0	0.0	100.0
GI1	83.3	0.0	0.0	16.7
GI2	n/a	n/a	n/a	n/a
HR	n/a	n/a	n/a	n/a
NPI	0.0	0.0	100.0	0.0
TI	0.0	0.0	100.0	0.0
WI	n/a	n/a	n/a	n/a
WV1	100.0	0.0	0.0	0.0
WV2	n/a	n/a	n/a	n/a
WV3	100.0	0.0	0.0	0.0
Mean	**n/a**	**n/a**	**n/a**	**n/a**

Table 3-5: Percentage of each supervised class by area for 0.5 km^2 area.

Survey	Fine sand	Macroalgae	Gravel	Cobble-boulder-bedrock
CR	0.4	9.1	59.8	30.7
DB1	2.2	0.5	25.8	71.4
DB2	5.5	0.9	19.3	74.3
GI1	5.2	7.0	54.8	33.0
GI2	15.2	4.8	35.1	44.8
HR	8.8	2.6	32.5	56.1
NPI	2.2	1.5	32.2	64.0
TI	0.0	15.4	75.1	9.5
WI	0.0	0.0	22.1	77.9
WV1	47.6	0.5	3.7	48.1
WV2	53.9	4.4	15.7	26.0
WV3	94.9	0.0	0.5	4.6
Mean	**19.7**	**3.9**	**31.4**	**45.1**

Table 3-6: Percentage of each supervised class by area for 1.0 km^2 area.

Survey	Fine sand	Macroalgae	Gravel	Cobble-boulder-bedrock
CR	0.7	16.3	55.8	27.2
DB1	3.8	1.1	27.3	67.7
DB2	3.6	0.6	24.5	71.3
GI1	9.4	8.1	45.8	36.6
GI2	9.5	9.6	49.7	31.1
HR	7.1	8.3	35.3	49.3
NPI	1.5	5.0	37.0	56.5
TI	0.0	31.7	61.3	7.0
WI	2.7	0.3	27.0	70.0
WV1	40.8	1.4	10.9	46.8
WV2	52.4	1.6	11.4	34.5
WV3	82.0	0.1	2.4	15.5
Mean	**17.8**	**7.0**	**32.4**	**42.8**

Table 3-7: Percentage of each supervised class by area for 1.5 km^2 area.

Survey	Fine sand	Macroalgae	Gravel	Cobble-boulder-bedrock
CR	1.2	19.3	53.7	25.8
DB1	3.6	1.1	28.9	66.4
DB2	4.4	0.7	24.7	70.2
GI1	11.6	6.2	39.4	42.9
GI2	9.3	9.2	48.1	33.4
HR	6.7	8.8	37.5	47.1
NPI	2.2	6.2	38.2	53.4
TI	0.0	33.5	58.0	8.4
WI	2.7	0.3	24.4	72.5
WV1	38.2	1.4	13.7	46.7
WV2	47.8	1.2	13.8	37.1
WV3	68.9	0.3	7.9	22.9
Mean	**16.4**	**7.4**	**32.4**	**43.9**

Table 3-8: Percentage of each supervised class by area for 2.0 km^2 area.

Survey	Fine sand	Macroalgae	Gravel	Cobble-boulder-bedrock
CR	1.3	20.2	51.4	27.0
DB1	4.7	1.1	26.8	67.3
DB2	4.7	1.1	26.8	67.3
GI1	10.5	7.3	42.3	39.9
GI2	10.5	7.3	42.3	39.9
HR	5.1	8.5	43.5	42.9
NPI	3.5	5.5	36.4	54.6
TI	0.9	30.2	56.2	12.7
WI	3.4	0.5	23.5	72.5
WV1	42.3	1.4	14.3	42.0
WV2	50.6	1.2	12.1	36.1
WV3	57.9	0.9	10.3	30.9
Mean	**16.3**	**7.1**	**32.2**	**44.4**

clustered around Cape Freels (Table 3-5 to 3-8). The spawning sites with the lowest occurrence of gravel were the northern sites; Deadman's Bay (DB1 and DB2), North Penguin Island (NPI), and wadaham Islands (WI) (Table 3-5 to 3-8).

At the 0.5 km^2 spatial scale fine sand accounted for 0% to 15.2% of the survey area of the spawning sites (Table 3-5). The occurrence of fine sand decreased at the 1.0 km^2 scale to 0 to 9.5% and remained constant at the 1.5 and 2.0 km^2 scales (Table 3-6 to 3-8). Fine sand was most abundant at the Gull Island sites (GI1 and GI2) off the west coast of Cape Freels and Hincks Rock (HR) site off the south coast of Cape Freels. At the 0.5 km^2 spatial scale fine sand accounted for 47.6% to 94.9% of the survey area of the non-spawning sites (Table 3-5). Therefore, it appears that fine sand is most abundant in the southern part of the survey area.

Fine sand consistently covered approximately 16% to 20% of the 0.5 km^2 to 2.0 km^2 survey areas. Over the same areas, gravel was also consistent at 31.4 to 32.4% (Figure 3-15). Between 0.5 km^2 and 1.0 km^2, the percent coverage of macroalgae increased from 3.9% to 7.0% (Table 3-5, 3-6, Figure 3-15). Between 1.0 km^2 and 2.0 km^2, macroalgae covered approximately 7% of the survey area (Table 3-6 to 3-8, Figure 3-15). Conversely the percent coverage of cobble-boulder-bedrock decreased from 45.1% to 42.8% between 0.5 km^2 and 1 km^2 (Table 3-5, 3-6, Figure 3-15). Between 1.0 km^2 and 2.0 km^2 cobble-boulder-bedrock covered approximately 44% of the survey area (Table 3-5, 3-6, Figure 3-15). Considering only the spawning sites, the percentage of each of the substrate types changed, but the pattern of occurrence was similar for all sites surveyed (Figure 3-16). Gravel accounted for 39% to 40%; fine sand accounted for 4% to 5%; macroalgae accounted for approximately 5% to 9% and cobble-boulder-bedrock

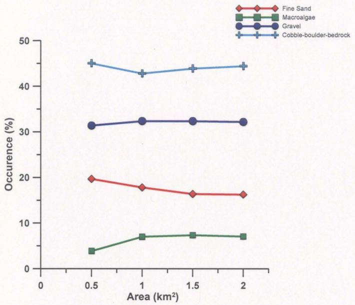

Figure 3-15: Percent coverage of each supervised class at four different spatial scales for each of the acoustically surveyed sites.

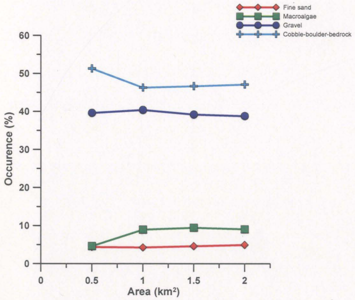

Figure 3-16: Percent coverage of each supervised class at four different spatial scales for the spawning sites.

accounted for approximately 40% to 45% of the spawning sites (Figure 3-16). Since the percent coverage of each of the supervised classes stabilized at 1.0 km^2 further analysis of the bathymetric structure of each site was continued only at this scale.

3.2. Demersal spawning habitat characteristics

In this section the temperature and the seabed morphology that characterizes the demersal spawning sites are presented. The depth and relief of the 1.0 km^2 acoustically surveyed area was compared to the point location of each of the spawning sites. In the following section the temperature trend of the Newfoundland Shelf taken from the Station 27 historic dataset is presented.

3.2.1. Depth

Overall, at the 1.0 km^2 spatial scale, macroalgae was acoustically detected at less than 20 m water depth, fine sand at greater than 25 m water depth, while gravel and cobble-boulder-bedrock were detected throughout the survey areas at varying water depths (Figure 3-17 to 3-24).

Along the acoustic survey track of the Cracker's Rock (CR) spawning site, macroalgae was found in shallow areas, predominantly at 10 to 18 m water depth (Figure 3-17). Gravel substrate was found throughout the survey area but less so at depths greater than 20 m. The cobble-boulder-bedrock substrate was detected at depth greater than 18 m. There was very little fine sand around the CR spawning site; small patches were detected at depth greater than 18 m.

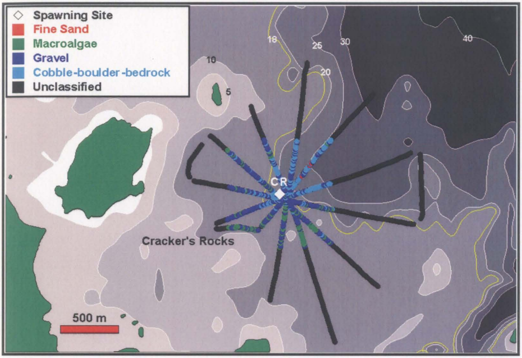

Figure 3-17: Supervised classification of the 1.0 km^2 acoustic survey from the Cracker's Rock (CR) spawning site.

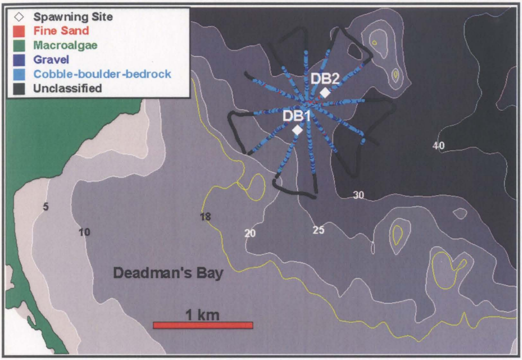

Figure 3-18: Supervised classification of the 1.0 km^2 acoustic survey from the Deadman's Bay (DB1 and DB2) spawning sites.

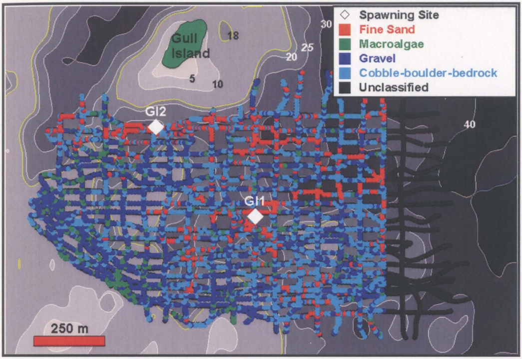

Figure 3-19: Supervised classification of the 1.0 km^2 acoustic survey from the Gull Island (GI1 and GI2) spawning sites.

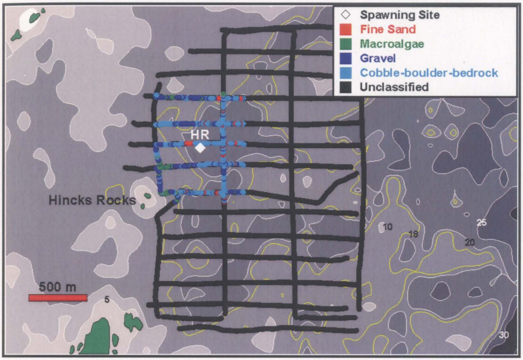

Figure 3-20: Supervised classification of the 1.0 km^2 acoustic survey from the Hincks Rocks (HR) spawning site.

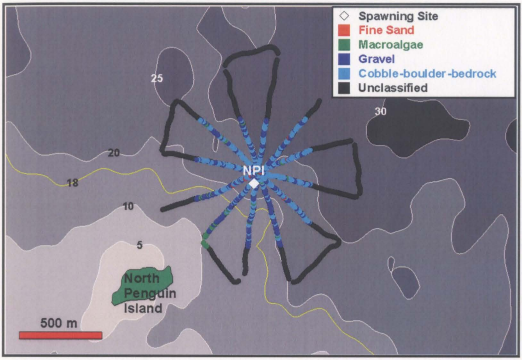

Figure 3-21: Supervised classification of the 1.0 km^2 acoustic survey from the North Penguin Island (NPI) spawning site.

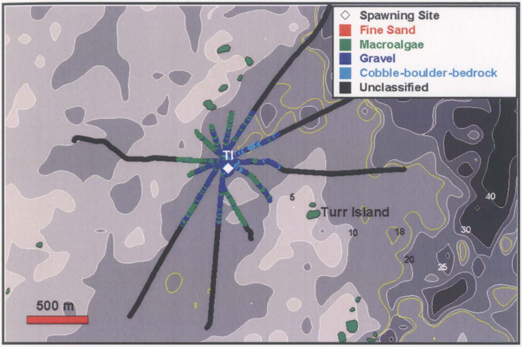

Figure 3-22: Supervised classification of the 1.0 km^2 acoustic survey from the Turr Island (TI) spawning site.

Figure 3-23: Supervised classification of the 1.0 km^2 acoustic survey from the Wadham Island (WI) spawning site.

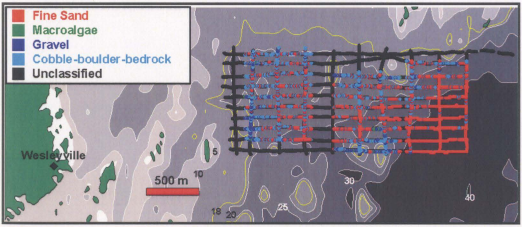

Figure 3-24: Supervised classification of the 1.0 km^2 acoustic survey from the Wesleyville (WV) non-spawning site.

The gravel and the cobble-boulder-bedrock substrates were detected throughout the Deadman's Bay (DB) survey area. The small amount of macroalgae that was present was found at 20 m water depth. Small deposits of fine sand were detected mainly at greater than 30 m water depths (Figure 3-18).

Within the Gull Island (GI) survey macroalgae was found at less than 18 m water depth and was clumped around the southwest part of the survey area where the seabed was shallow, approximately 10 m water depth (Figure 3-19). Gravel substrate was found throughout the survey area with concentrations in the western part of the survey area in less than 25 m water depth. Cobble-boulder-bedrock was also found throughout the survey area but was more prominent in the southeast at 20-25 m water depth. Fine sand was detected at greater than 20 m water depth.

At the Hincks Rock (HR) site, cobble-boulder-bedrock was detected at water depths of greater than 20 m, while gravel was detected at water depths shallower than 18 m (Figure 3-20). Macroalgae was detected near 10 m water depth. Fine sand was found in small patches throughout the survey area at water depths greater than 20 m.

Along the North Penguin Island (NPI) survey track, macroalgae occurred at water depths between 10 m and 18 m. Fine sand occurred mainly at water depths greater than 25 m. The gravel and cobble-boulder-bedrock substrates occurred throughout the survey area. Gravel concentrations were detected at water depths greater than 20 m (Figure 3-21).

Macroalgae and gravel were abundant throughout the Turr Island (TI) survey (Figure 3-22). Macroalgae was found between 10 and 20 m water depth. Gravel was detected at water depth greater than 20 m. Cobble-boulder-bedrock was detected near 18 m water depth. Fine sand was not detected within the 1.0 km^2 area of this acoustic survey.

The Wadham Islands (WI) survey area was dominated by the cobble-boulder-bedrock substrate (Figure 3-23). Patches of gravel were also detected between the cobble-boulder-bedrock throughout the survey. Very small amounts of macroalgae and fine sand were also detected throughout the survey area; however, the occurrence of these substrates was sporadic.

Finally, at the Wesleyville (WV) site, fine sand was concentrated at the southeast part of the survey area, while cobble-boulder-bedrock dominated the western portion of the survey area (Figure 3-24). Some gravel was interspersed with the cobble-boulder-bedrock substrate.

The bathymetric value of each of the spawning sites was plotted against the mean depth of the 1.0 km^2 acoustically surveyed area surrounding the site (Figure 3-25). The bathymetric values of the spawning sites were greater than the mean depth and the standard deviation of the 1.0 km^2 survey area. The deviation of the depth of the point locations from the mean depth of the survey area increased as the depth of the point location of the sites increased. This indicates that spawning may be occurring in bathymetric depressions. These depressions become more pronounced with depth. Sand and gravel sediments can collect in depressions, which may explain why spawning occurs in the depressions.

The General Linear Model (GLM) was used to test for differences in the depth distributions of the four supervised classes for each of the 1.0 km^2 acoustically surveyed spawning sites, with depth as the dependent variable and class as the independent

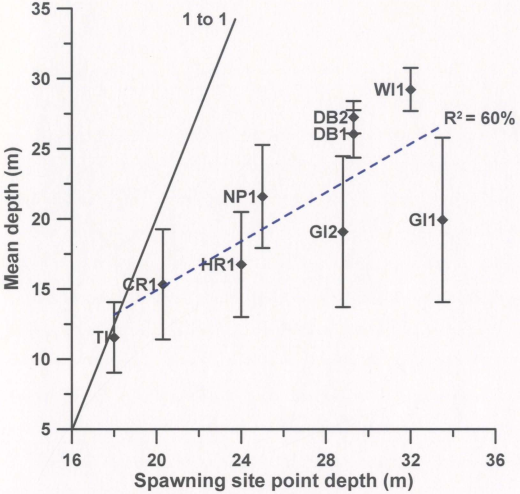

Figure 3-25: The bathymetric value of the spawning site vs. the mean depth and standard deviation of the 1 km^2 area surrounding the spawning sites. Black diamonds denote point depths. The dashed blue line is the regression line with the equation Y = 0.87X - 2.47 (R^2=0.60). The solid line is the one-to-one correspondence line.

variable. Overall, the depths of each of the supervised classes were statistically different ($F_{[3, 8696]} = 2061.91$, $p < 0.0001$) (Table 3-9). The mean depth of the macroalgae was 12.9 m, gravel was 17.7 m, cobble-boulder-bedrock was 23.2 m, and fine sand was 27.0 m (Table 3-9).

At the Cracker's Rock (CR) site, the Gull Island sites (GI1 and GI2), as well as the Hincks Rock (HR), and Turr Island (TI) sites, the mean depths of the four supervised classes were statistically different (Table 3-9; Figure 3-26). However, the depths of the classes at the other sites were not statistically different for some or all of the seabed habitats (Table 3-9; Figure 3-26). At the Deadman's Bay 2 site (DB2), the Duncan and GT2 tests indicated no statistically significant difference in depth between any of the four supervised classes (Table 3-9). Similarly, at the Wadham Islands (WI) site, there was no significant difference between the depths of the four classes (Table 3-9). At the Deadman's Bay 1 (DB1) site, only macroalgae was statistically different from the other three substrates. At the North Penguin Island (NPI) site, the mean depths of the fine sand and cobble-boulder-bedrock substrates were not statistically different, but they were statistically different from the macroalgae and gravel substrates.

The bathymetric values of each spawning site were compared to the mean depth of the gravel substrate (Figure 3-27). The bathymetric values at seven of the nine spawning sites were similar to the mean depth of the gravel substrate. However, the bathymetric values of the Gull Island sites (GI1 and GI2) were greater than the mean depths of the gravel substrate. The substrate from these two sites consisted primarily of fine sand rather than gravel.

Table 3-9: Differences in mean depth of the four supervised classes at each of the nine spawning sites over the 1.0 km^2 acoustically surveyed area using the GLM with the Duncan and GT2 tests. Means with the same letter are not significantly different. Class 1=fine sand; Class 2 = macroalgae; Class 3 = gravel; Class 4 = cobble-boulder-bedrock. There was no fine sand present at the TI site.

		Mean Depth (m)								Degrees of Freedom			
Site	**Bathymetric value**	**Class 1**	**Duncan/GT2 Grouping**	**Class 2**	**Duncan/GT2 Grouping**	**Class 3**	**Duncan/GT2 Grouping**	**Class 4**	**Duncan/GT2 Grouping**	**Model**	**Error**	**F-value**	**p-value**
CR	20.3	23.3	D	11.4	A	14.6	B	18.9	C	3	562	143.12	<0.0001
DB1	29.3	26.8	B	23.1	A	25.8	B	26.2	B	3	520	9.72	<0.0001
DB2	29.3	27.4	A	26.4	A	27.2	A	27.2	A	3	523	0.59	0.6191
GI1	33.5	28.0	D	15.0	A	17.1	B	22.5	C	3	2054	475.26	<0.0001
GI2	28.8	27.5	D	15.5	A	16.4	B	21.9	C	3	981	308.18	<0.0001
HR	24.0	20.0	D	9.8	A	15.0	B	18.7	C	3	529	219.77	<0.0001
NPI	25.0	23.0	C	15.1	A	20.7	B	22.7	C	3	580	58.45	<0.0001
TI	18.0	n/a	n/a	9.1	A	12.5	B	14.9	C	3	508	266.72	<0.0001
WI	32.0	30.1	A	29.0	A	28.9	A	29.3	A	3	326	2.2	0.0879
Mean	**26.7**	**27.0**	**D**	**12.9**	**A**	**27.7**	**B**	**23.2**	**C**	**3**	**8696**	**2061.91**	**<0.0001**

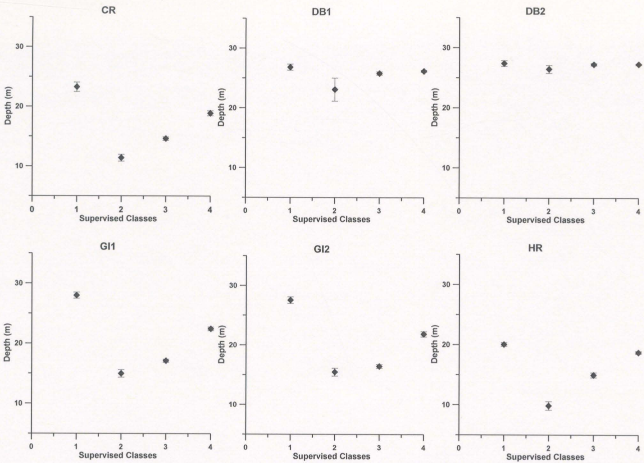

Figure 3-26: Mean depth and 95% CI for each supervised class within 1.0 km^2 of the spawning site. Class 1=fine sand; Class 2 = macroalgae; Class 3 = gravel; Class 4 = cobble-boulder-bedrock.

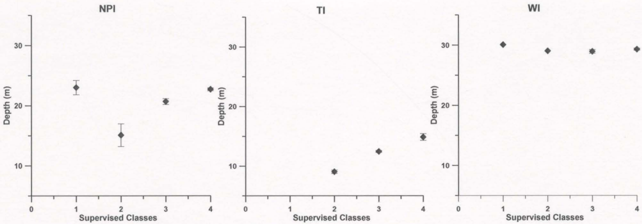

Figure 3-25: Continued.

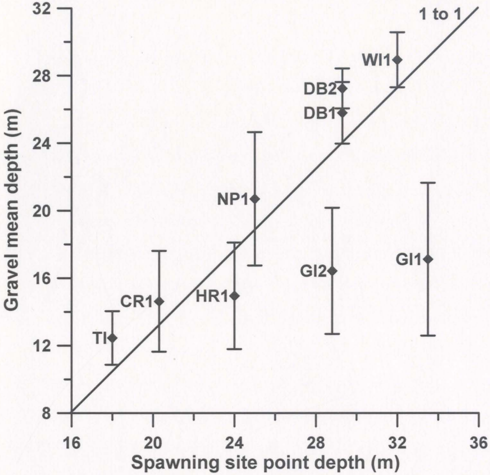

Figure 3-27: The bathymetric value of the nine spawning sites vs. the mean depth of gravel for each spawning site and the standard deviation of the 1.0 km^2 acoustically surveyed area. The straight line is the one to one correspondence line.

3.2.2. Relief

Wilcoxon scoring and Kruskal-Wallis tests were performed to determine the statistical differences of the relief between the supervised classes at each of the spawning sites (Table 3-10). The mean absolute relief of the four supervised classes at the Cracker's Rock site (CR), the Deadman's Bay sites (DB1 and DB2), and the North Penguin Island site (NPI) were not statistically different, each ranging between 0.02 to 0.04 m/km (Figure 3-28). The mean absolute relief at the Wadham Islands (WI) site was the lowest of all the spawning sites ranging between 0.015 m/km and 0.02 m/km (Figure 3-28). The relief of the supervised classes at the Gull Island sites (GI1 and GI2), the Hincks Rock (HR) site, and the Turr Island (TI) site were statistically different and had the greatest range in mean relief between supervised classes. For each of these sites, fine sand had the lowest relief, except at the TI site where there was no fine sand present (Figure 3-28), and macroalgae had the highest relief. By comparison, the relief of the gravel and the cobble-boulder-bedrock substrates was lower than that of the macroalgae substrate but higher than the fine sand substrate relief (Figure 3-28).

Overall, the relief was greatest at the southern spawning sites; Cracker's Rock (CR), Gull Island (GI1 and GI2), and Turr Island (TI), which were all clustered around Cape Freels, and the Hincks Rock site (HR), which was further south. These sites had the greatest variation in relief between classes. Variation in relief between classes decreased at the northern spawning sites; Deadman's Bay (DB1 and DB2), North Penguin Island (NPI) and Wadham Islands (WI).

Table 3-10: Differences in mean absolute relief (m/km) of the four supervised classes at each of the nine spawning sites over the 1.0 km^2 acoustically surveyed area using Wilcoxon scoring and the Kruskal-Wallis tests. Class 1=fine sand; Class 2 = macroalgae; Class 3 = gravel; Class 4 = cobble-boulder-bedrock.

Survey	Fine Sand	Macroalgae	Gravel	Cobble-boulder-bedrock	Df	N	Chi 2	p
CR	0.040	0.033	0.039	0.033	3	566	3.966	0.2652
DB1	0.026	0.025	0.027	0.022	3	524	7.071	0.0691
DB2	0.026	0.033	0.025	0.021	3	527	4.8632	0.1821
GI1	0.039	0.106	0.091	0.078	3	2058	127.1648	<0.0001
GI2	0.031	0.113	0.094	0.081	3	985	97.7517	<0.0001
HR	0.017	0.086	0.047	0.020	3	533	88.9162	<0.0001
NPI	0.030	0.037	0.027	0.023	3	584	9.7881	0.0205
TI	-	0.052	0.036	0.022	3	511	27.038	<0.0001
WI	0.015	0.020	0.019	0.017	3	330	2.2816	0.516
Mean	0.028	0.056	0.045	0.035	-	-	-	-

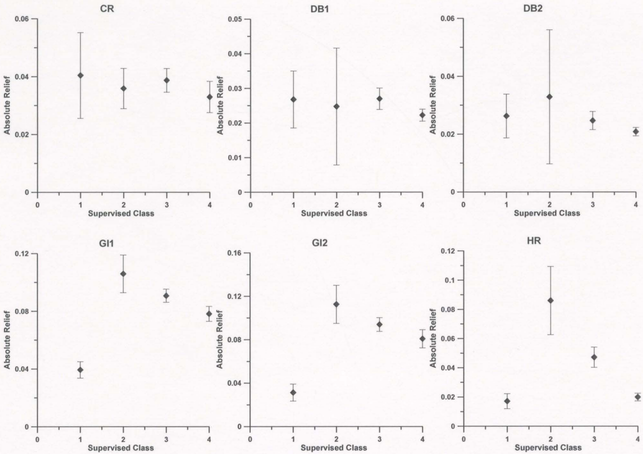

Figure 3-28: Mean absolute relief (m/km) and 95% CI for each supervised class within 1.0 km^2 of the spawning site: Class 1=fine sand; Class 2 = macroalgae; Class 3 = gravel; Class 4 = cobble-boulder-bedrock.

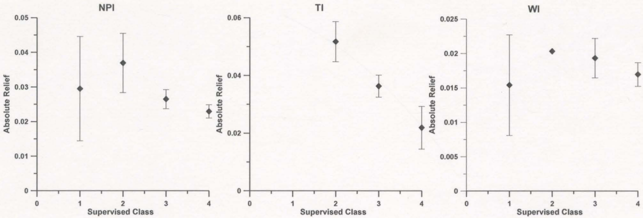

Figure 3-28: Continued.

3.2.3. Temperature

The minimum temperature required for successful capelin spawning to occur is 2°C (Carscadden et al., 1989). Based on temperature profiles from historical temperature data from Station 27, the 2°C isotherm occurs at water depths that are ≤40 m during June, July and August (Figure 3-29).

The 2°C June isotherm occurred at 28 to 29 m water depth in 1960-1999 but at 38 m from 2000-2005. The June surface water temperature for the past 45 years has been more stable varying between 5.0 and 5.6°C (Table 3-9; Figure 3-29). The depth of the 2°C July isotherm varied between 30 m and 38 m from 1960-2005. Surface water temperatures in July ranged between 9.5 and 10.8°C for this time period. The depth of the August 2°C isotherm varied from 35 m in the 1960s, 42 m in the 1970s, 38 m in the 1980s, to 36 m from 1990 to 2005. Throughout June and July of 1990 to 2005, surface water temperatures along the northeast coast of Newfoundland were less than 12°C. By August, however, water temperatures near the surface exceeded 12°C, the upper limit for capelin spawning. In the 1960s, water shallower than 7 m was warmer than the 12°C isotherm, while in the 1970s, the 12°C isotherm occurred in water less than 11 m deep and less than 6 m deep in the 1980s. In the 1990s, the 12°C isotherm lowered to 10 m water depth, and for 2000 to 2005, it was at 12 m water depth (Figure 3-29)

In 2004, Penton (2006) observed spawning at all spawning sites except for the two Deadman's Bay sites (DB1 and DB2). Thermisters were placed at each of the known spawning sites. For the Deadman's Bay sites, the thermister was placed at a point equidistant between DB1 and DB2 (Table 3-11). Due to technical difficulties, the temperature data for the North Penguin Island (NPI) site was lost. The mean bottom

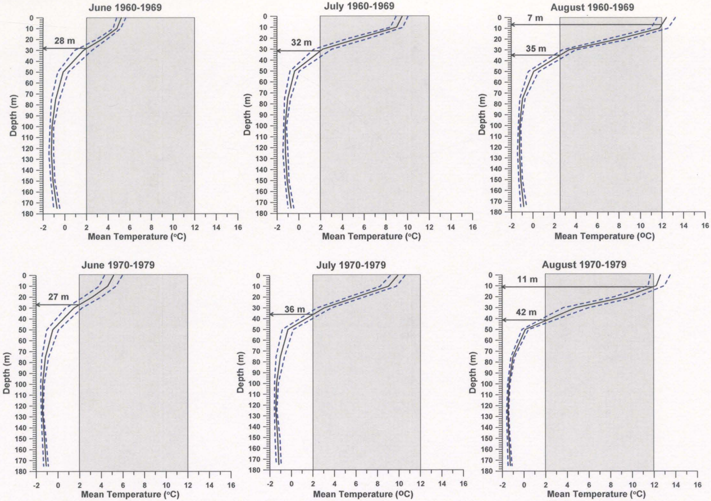

Figure 3-29: Mean vertical temperature profile (0 to -175 m) (solid lines) and 95% CI (dotted blue lines) from Station 27 for June, July, and August from 1960-2005. The temperature range of the water for demersal capelin spawning is ≥ 2°C and ≤12.0°C, which is represented by the grey shading. Upper and lower water depths for this temperature range are indicated.

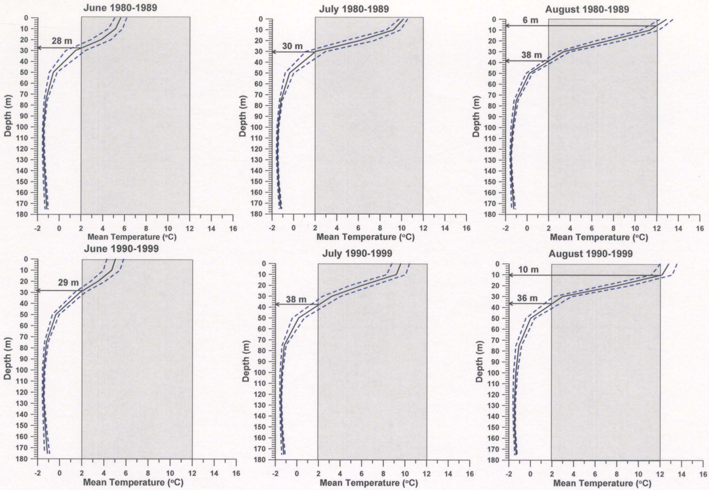

Figure 3-29: Continued

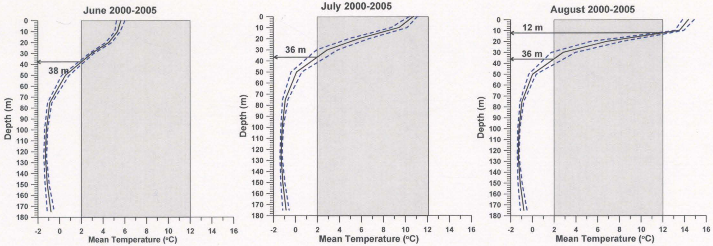

Figure 3-29: Continued

Table 3-11: Spawning site bathymetric value, thermister depth and mean temperature (°C).

Spawning Site	Bathymetric value (m)	Thermister Depth (m)	Mean Temperature (°C)	Comments
CR	20.3	19.5	5.5	Retrieved
DB1 and 2	29.3	28.8	3.6	Retrieved
GI1	33.5	33	2.4	Retrieved
GI2	28.8	28.3	3.5	Retrieved
HR	24	23.5	4.7	Retrieved
NPI	25	24.5	n/a	Lost
TI	18	17.5	2.7	Retrieved
WI	32	31.5	5.1	Retrieved

Table 3-12: Mean vertical temperature (°C for 0 to 175 m water depth) from Station 27 for June, July, and August 1960-2005.

Depth	*1960-1969*			*1970-1979*			*1980-1989*			*1990-1999*			*2000-2005*		
	June	July	August	June	July	August	June	July	August	June	July	August	June	July	August
0	5.2	9.5	12.4	5.2	9.9	12.6	5.6	10.1	12.9	5.0	9.6	12.8	5.6	10.8	14.4
10	4.8	9.0	11.8	4.6	9.0	12.2	5.1	9.2	11.3	4.7	9.2	12.2	5.3	9.5	13.6
20	3.4	5.6	7.9	3.2	6.0	9.4	3.8	6.1	7.4	3.4	6.0	7.9	4.5	5.8	6.8
30	1.7	2.2	3.4	1.5	3.1	4.8	1.5	2.0	3.4	1.8	3.2	3.0	3.0	2.9	2.9
50	-0.1	-0.4	0.1	-0.5	-0.3	0.1	-0.6	-0.4	0.2	-0.4	0.1	0.0	0.5	0.1	0.0
75	-0.8	-1.0	-1.0	-1.1	-1.0	-1.0	-1.2	-1.2	-1.0	-1.2	-1.2	-1.1	-0.9	-0.9	-1.0
100	-1.2	-1.3	-1.2	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.2	-1.2	-1.2
125	-1.2	-1.2	-1.2	-1.4	-1.4	-1.5	-1.4	-1.5	-1.5	-1.5	-1.5	-1.5	-1.3	-1.3	-1.3
150	-1.1	-1.1	-1.1	-1.2	-1.3	-1.4	-1.3	-1.4	-1.4	-1.3	-1.4	-1.5	-1.1	-1.1	-1.1
175	-0.7	-0.7	-0.8	-1.1	-1.2	-1.3	-1.1	-1.2	-1.2	-1.1	-1.2	-1.3	-0.8	-0.9	-0.8

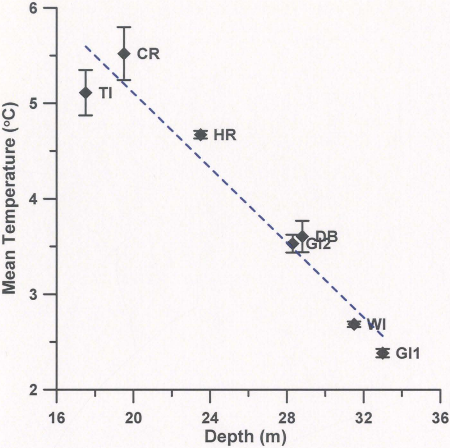

Figure 3-30: Plot of the relationship between depth and mean bottom temperature with the 95% CI (vertical black bars) of the temperature at each of the demersal spawning sites in 2004. Regression line (dashed blue line) with the equation Y = -0.20X + 9.02 (R^2=0.94).

temperature at the known spawning sites ranged between 2.4°C and 5.5°C (Figure 3-30). The seabed temperatures were highly correlated with depth (R^2 = 94%). Temperatures were coldest at the deepest spawning site, Gull Island 1 (GI1) (33 m deep), with a mean of 2.4°C. The warmest temperature with a mean of 5.5°C was recorded at the Cracker's Rock (CR) spawning site, one of the shallowest sites with a depth of 19.5 m. Spawning events at these sites occurred between July 22 and August 17 (Table 3-12; Figure 3-30).

4. Discussion

The results of this study are used to address the proposed research questions. First, how effective was the acoustic system at identifying and classifying the demersal capelin spawning habitats on the basis of their acoustic signatures? Both the unsupervised classification and the supervised classification were examined to determine how useful each was for identifying the acoustic signature of the spawning substrate at each site. The supervised classification was also examined to determine how successful it was at identifying the acoustic signatures for other substrates present within the study area. Next, the potential for mapping new spawning habitats using the acoustic signatures identified from this study was considered.

Secondly, what are the physical factors that constitute demersal capelin spawning habitats in coastal Northeast Newfoundland along the Straight Shore and how do the results compare to the conceptual model? The demersal spawning sites that were investigated in this study were characterized in terms of the water temperature during spawning, bathymetry, depth, and substrate grain-size. Comparisons were then made between the results of this research, previous studies of demersal capelin spawning habitats on the Southeast Shoal and demersal spawning studies done in Iceland and the Barents Sea. The demersal sites were also compared to beach spawning sites along the Straight Shore, at Bellevue Beach in Newfoundland, in Greenland, and in Alaska. These comparisons were followed by a discussion on the surficial sediment characteristics of the seabed within the study area and the sediment size class that is associated with the spawning sites. The results were then used to reformulate the conceptual model.

This chapter is concluded with a discussion on potential future research for locating and identifying new demersal capelin spawning habitats in Newfoundland and other areas where capelin are known to occur but where demersal spawning has not yet been observed or discovered.

4.1. Acoustic seabed classification

Methods employed to examine demersal capelin spawning habitats include temperature (Nakashima & Wheeler 2002), depth (Saetre & Gjosaeter 1975) and spawning substrate (Carscadden et al., 1989; Nakashima and Wheeler, 2002; Pahlke, 1985; Saetre and Gjosaeter, 1975), and analysis of fish stomach contents (Carscadden et al. 1989). This study has used normal incidence acoustic methods to obtain detailed information about demersal capelin spawning habitats off the northeast coast of Newfoundland. Acoustic methods have been employed elsewhere to identify benthic biotopes and to monitor anthropogenic activities such as dredging and dredge spoil disposal (Foster-Smith et al., 2004; Freitas et al., 2003a; Wienberg and Bartholoma, 2005).

4.1.1. Unsupervised classification

Using the unsupervised classification method three classes were routinely found at each of the spawning sites. One acoustic class was detected at the Wadham Islands site and two classes were found at the non-spawning sites. For most of the spawning sites, one class accounted for nearly 50% of the survey area. For the Gull Island surveys, the percent coverage of the three unsupervised classes was nearly equal. It is possible that the Gull Island survey has diverse substrates.

Depth-dependence in the Q-values, particularly Q1, has been noted in several studies (Anderson et al., 2002; Foster-Smith et al., 2004; Hutin et al., 2005). In this study, there is a depth-dependence in the Q-values and the unsupervised classes for all demersal survey sites except at the Deadman's Bay 2 (DB2) and Wadham Islands (WI) sites, both of which have little relief. At DB2, three depth-independent classes were detected. Although the depths of the unsupervised classes at the Deadman's Bay 1 (DB1) site were statistically different, it is not likely an artifact of the QTC classification because DB1 and DB2 sites were part of the same survey and there was no statistical difference in the Q-values or the classes at the DB2 site.

Benthic habitats and sediment structures are known to change with depth (Hutin et al., 2005). This study suggests a correlation between sediments and spatial patterns of benthic habitats with depth. At several locations, macroalgae beds, which have a distinct acoustic signature, were observed from ROV images and were found in less than 20 m water depth. Macroalgae require sunlight to grow and therefore would be expected to be found in the shallowest part of the surveys where there is sufficient light penetration through the water. Fine sand was found at depth of 25 m or greater, while gravel and bedrock substrates were found throughout the depths sampled.

The Straight Shore offshore region is dominated by postglacial sediments (Shaw et al., 1999). The movement by wave action of sediments on the seabed occurs at intervals that are depth dependent. Ten second wave periods affect sediments that are in $\leq$38 m water depth, while 12 second wave periods have a significant effect on sediments on the seabed down to 55 m water depth (Shaw et al., 1999). Fine sand is more mobile than gravel substrates. Therefore, fine sand is expected to be more easily carried in suspensions and deposited into deeper water where wind and wave action are dissipated.

Gravel is less mobile but may have been reworked since glacial deposition.

4.1.2. Supervised classification

In this study, the QTC IMPACT supervised classification process was used to characterize the substrate at each of the spawning sites. Through the supervised classification four substrate habitats were identified. These included fine sand, gravel (the spawning substrate), cobble-boulder-bedrock, and macroalgae. More substrate habitats may have been present within the study area, but the supervised method classifies acoustic signals only according to the signatures that are within the training dataset, which was limited by the available ground-truth data. However, the unsupervised classification is not restricted by ground-truth data, and each survey produced one to three classes, each of which could be any one of the four substrate types identified in the supervised classification. At many of the spawning sites, capelin spawned on gravel substrates, and the supervised acoustic gravel class was detected at these sites. However, both the Gull Island (GI) spawning sites were associated with the supervised acoustic fine sand class. This was consistent with the grab samples taken from both GI sites. The samples taken from the Gull Island 1 (GI1) site were composed of fine to very coarse sand. At the Gull Island 2 (GI2) site, there was a greater variety in the grab samples, some consisting purely of sand and others consisting largely of pebble gravel material with minor amounts of sand. The variability of the sediments at each of the sites was identified through supervised classification. At the GI2 site, the gravel acoustic class is in close proximity to the spawning site, whereas at the GI1 site only the fine sand acoustic class was represented.

Off the Straight Shore, capelin spawn demersally on poorly-sorted sand and gravel substrates at nine known sites. To estimate the scale or dimensions of the known spawning beds and the potential area available for spawning the distribution of the supervised classes was analyzed for areas of 0.05 km^2 (the area of the point location of the spawning site), 0.5, 1.0, 1.5 and 2.0 km^2. At 0.05 km^2, gravel covered 100% of the area for three of the spawning sites, and fine sand covered 83.3% of the area at the Gull Island 1 (GI1) site. Gravel substrate was associated with spawning at seven of the nine spawning sites. At the two Gull Island sites, spawning was associated with sand. No acoustic class was detected at the other sites at the 0.05 km^2 scale, probably because the acoustic track lines did not intercept the point position of those spawning sites. This failure to intercept is one of the limitations of normal incidence acoustics. The footprint of the acoustic signal covers a small area along the survey track, which varies with depth, and interpolation is required for the space in between survey track lines.

Between 0.05 km^2 and 1.0 km^2, there were significant changes in the occurrence of each of the four substrate types detected at each of the spawning sites. However, the overall occurrence of the four substrates did not change substantially when the spatial area increased to 1.5 and 2.0 km^2. Therefore it is likely that the spawning beds are greater than 0.05 km^2 but $\leq$1.0 km^2. The estimated size range of the spawning beds reflects the variation in the occurrence of each substrate type at each site. At 1.0 km^2, the occurrence of gravel ranged between 24.5% and 61.3%. Therefore the occurrence of gravel could be used to estimate the size of the spawning bed at each site except in the case of the Gull Island (GI1 and GI2) sites, where spawning occurred on fine sand. At the GI1 and GI2 sites, fine sand accounted for 9.4% and 9.5% respectively, while gravel accounted for 45.8% and 49.7%. Within this survey area, spawning does occur on fine sand but could potentially occur on the gravel substrate.

The supervised acoustic gravel class accounted for 32% of the survey area for all sites at the 1.0 km^2 scale. Disregarding the non-spawning site survey, the gravel class covered 40% of the area surveyed. This pattern suggests that the seabed off the Straight Shore is suitable for demersal capelin spawning. One third of the survey area had suitable gravel substrate for spawning, and gravel was more abundant at sites with greater seabed relief. The Cracker's Rock (CR) site, the Gull Island sites (GI1 and GI2), and the Turr Island (TI) site, which are all clustered off Cape Freels, have the highest occurrence of the gravel supervised acoustic class. The four sites have the greatest variation in relief among the four identified substrate types and the greatest mean absolute relief for the gravel substrate. The bathymetric value of these sites also had the greatest deviation from the mean of the gravel substrate. It is possible that the variable relief of this area may provide depressions for mobilized gravel to settle resulting in higher proportions of the substrate than at the other sites. The depressions may be occurring in the troughs of gravel ripples that occur along the Straight Shore in less than 80 m water depth (Shaw et al., 1999).

When grab samples could not be collected, the ROV was deployed to determine the bottom type. In many cases, the images from the ROV showed that coarse sand and pebbles were present but in small patches surrounded by cobble and boulders too big for the grab. On occasion, the ROV proved to be inadequate for the survey area. The ROV was a lightweight (approximately 4-7 kg) system that was often taken off-course by strong currents. Another issue with the ROV was that there was no proper position data available for the camera, geographic locations of the ROV images was based on GPS coordinates of the. Since the cable from the on-board controls to the camera was very long the recorded position of the ROV was not precise.

4.2. Demersal capelin spawning habitat characteristics

4.2.1. Demersal spawning

Capelin that spawn demersally off the Straight Shore do so on sand and gravel, just as those capelin in the coastal waters off Bellevue Beach do (Nakashima and Wheeler, 2002). In Newfoundland, capelin spawning substrate along beaches ranges in size from 2 mm to 15 mm (Nakashima and Wheeler, 2002; Templeman, 1948). Demersal spawning substrate from this study ranged from 0.125 mm to 32 mm. These are larger size ranges than the substrate size range recorded from the Southeast Shoal (0.5 to 2.2 mm). It is important to note however, that the substrate from the Southeast Shoal is based on recordings from the stomach contents of haddock and capelin. The particles were swallowed along with capelin eggs; therefore, this finding is probably not a representative measure of grain-size from the spawning beds on the Southeast Shoal (Saetre and Gjosaeter, 1975).

The water temperatures for spawning in the coastal waters off Bellevue Beach are generally higher (3.5-11.9°C) than the temperatures on the demersal site found off the Straight Shore (2.4-5.5°C). Demersal spawning sites off Bellevue Beach are shallower (10-20 m water depth) than the sites found off the Straight Shore (18-33 m water depth). Demersal spawning on the Southeast Shoal occurred in cooler water temperatures (0.5-4.2°C) and at greater depths (40-80 m) than the demersal sites on the Straight Shore (Carscadden et al., 1989; Saetre and Gjosaeter, 1975; Thors, 1981).

The Barents Sea capelin spawn at slightly cooler temperatures (1.5°C to 4.0°C)

(Saetre and Gjosaeter, 1975; Thors, 1981) than other demersal spawning populations. Icelandic capelin spawn demersally in water that was 5°C to 7°C (Thors, 1981), which is warmer than the temperature range at which capelin spawn on the northeast coast of Newfoundland (2.4°C to 5.5°C).

In Iceland, the Barents Sea, and offshore Newfoundland, spawning has occurred at greater depths than those that have been recorded in coastal Newfoundland, but at similar depths spawning depths on the Southeast Shoal spawning (40 m to 80 m). Capelin spawn at depths that range from 5 m to 90 m off the coast of Iceland, and from 10 m to 280 m in the Barents Sea. Spawning off the coast of Iceland and in the Barents Sea may not be comparable to spawning the Straight Shore and to other demersal spawning on the Newfoundland Shelf because the water column temperature profile is governed by different water masses. The depth limits of the warm surface and bottom layers (> 0°C) and the Cold Intermediate Layer (CIL, < 0°C) may be different from those on the Newfoundland Shelf. Capelin may spawn in the warm bottom layer below the CIL in Iceland, the Barents Sea, and offshore Newfoundland.

The demersal spawning temperatures of the coastal waters off the Straight Shore, Bellevue Beach, and Iceland fall within the range outlined in the conceptual model, but the Southeast Shoal and Barents Sea spawning temperatures are cooler. The spawning temperature difference may arise from variations in oceanographic conditions at each location such as the influence of onshore and offshore winds, solar radiation, and water mass characteristics. Therefore, capelin may prefer to spawn temperatures that range between 2°C and 12°C but are able to spawn at temperatures beyond this range. However, spawning outside the 2°C to 12°C temperature range can impact egg and larval development (Carscadden and Frank, 2002; Carscadden et al., 2001; Carscadden et al., 1997; Davoren et al., 2006; Nakashima and Wheeler, 2002; Templeman, 1948).

4.2.2. Beach spawning

In the NSERC study, as with the study done in the coastal area of Bellevue Beach by Nakashima and Wheeler (2002), beach spawning was compared to demersal spawning. At the Bellevue Beach, beach and demersal sites, spawning took place within the 2°C to 12°C water temperature range proposed in the conceptual model (Nakashima and Wheeler, 2002). In the NSERC study, however, it was discovered that beach spawning occurred in warmer water temperatures. The average daily water temperature at the Capelin Cove and Lumsden beach spawning sites was 11.2°C and 11.4°C (Andrews, 2005), but those values were still within the temperature range proposed in the conceptual model. Spawning at the demersal sites occurred in lower water temperatures (2.4-5.5°C). The beach spawning temperatures at the Straight Shore sites may be higher than the temperatures recorded at the Bellevue site but they are similar to spawning temperature recorded near Vancouver Island (10-13°C) and higher than those recorded for Alaska and Greenland (5-10°C and 1.9-8.5°C respectively) (Pahlke, 1985). However, since the beach water temperatures are influenced by solar radiation, the range of the temperatures at the various beach spawning areas would be expected because of the differences in latitude which reflect the difference in the amount of available solar radiation that each location receives. Variation in water temperature is also influenced by different water masses that govern the different spawning areas.

The substrate at the Straight Shore beach sites and demersal sites are composed of sand and gravel. The range of grain-sizes at the demersal sites is larger (0.15-32 mm, fine sand to coarse pebble) than on the beach (0.62-28 mm, medium sand to coarse pebble). The grain-size range from both the demersal and beach spawning sites at the Straight Shore exceeds the grain-size range proposed in the conceptual model and is also larger than the range reported for other Newfoundland beaches (2-15 mm) and for Alaskan beaches (2-20 mm) (Carscadden et al., 1989; Jangaard, 1974; Nakashima and Wheeler, 2002; Pahlke, 1985; Saetre and Gjosaeter, 1975; Templeman, 1948; Thors, 1981).

It is difficult to compare the surficial sediment structure of the demersal and beach spawning sites from the Straight Shore with that of demersal and beach spawning locations elsewhere because of the different ways in which sediment size distribution has been reported. In some cases the median substrate size was reported, as was the case of spawning substrate from the Barents Sea (Saetre and Gjosaeter, 1975). However, in the studies conducted at the beach and demersal site around Bellevue Beach and at the demersal spawning sites off Iceland, the mean was used to express the range in grain-size (Nakashima and Wheeler, 2002; Thors, 1981). Although the spawning sediment was summarized with the mean grain-size, Thors (1981) emphasized that eggs were found on finer sediments and showed the entire grain-size distribution on a Gravel-Sand-Mud (GSM) triangle. Using just the median or the mean to express the size distribution of the sediment at the spawning sites can give different limits than full size range to the sediment size range (Table 4-1). In the present study, the description of the spawning substrate was based on the grain-size distribution from the cumulative percent distribution curve for each sample at each site. The cumulative percent distribution curve

Table 4-1: Description of the sediment size range using different measurement scales.

Scale	Demersal			Beach			Non-spawning		
	Φ	mm	Description	Φ	mm	Description	Φ	Mm	Description
5-95%	2.55 to -4.80	0.17 to 28.00	Fine sand to coarse pebble	1.30 to -4.85	0.40 to 29.00	medium sand to coarse pebble	3.00 to -4.80	0.125 to 28.00	fine sand to coarse pebble
Median	2.05 to -4.70	0.24 to 26.00	Fine sand to coarse pebble	-0.70 to -3.60	1.80 to 12.50	very coarse sand to medium pebble	2.90 to 2.00	0.135 to 0.25	fine sand to fine pebble
Mean	1.95 to -3.00	0.26 to 8.00	medium sand to medium pebble	-0.47 to -2.33	1.40 to 4.90	very coarse sand to fine pebble	2.92 to 0.27	0.135 to 0.81	fine sand to coarse sand

was based on several statistical measures which include the mode, graphical median, graphical mean, sorting (graphical standard deviation), skewness and kurtosis. Based on these analyses, the range of sediments was reported as the middle 90% of the cumulative distribution curve from all samples taken from all demersal spawning sites. This method of analysis was also used for the beach spawning sites and the non-spawning site.

4.2.3. Surficial sediments

Shaw et al. (1999) described the inner Newfoundland shelf from Cape Freels to Fogo Island. The area where the demersal spawning sites are located was described as a wave- and current-dominated zone (Shaw et al., 1999). This zone extends from approximately 60 m water depth to the coast and is 20 km wide off the Straight Shore (Shaw et al., 1999). Movement by wave action of sediments on the seabed occurs at intervals that are depth dependent. Ten-second wave periods affect sediments at water depths that are ≤ 38 m, and 12-second wave periods have a significant effect on sediments on the seabed down to 55 m water depth (Shaw et al., 1999). Some of the areas have mobile clastic sediment with gravel ripples, sand dunes, and sand ribbons, while other areas have poorly-sorted pebble-cobble-boulder gravel from intermittently mobile armoured lags which are over glacial diamicton or on top of deposits of finer sediment (Shaw et al., 1999). The observations made by Shaw et al. (1999) is consistent with the analysis of the ROV images from the North Penguin Island (NPI), and Wadham Island (WI) sites which show areas of pebble-cobble-boulder on top of deposits of finer sediment. The potential for reworking of source material such as glacial diamicton and other ice-contact deposits is greatest in shallow water (Shaw et al., 1999). In the case of glacial diamicton, the energy required for reworking is found only in the intertidal zone.

In deeper water, reworking by waves creates an immobile armoured lag of boulders and cobbles which impedes the winnowing process (Shaw et al., 1999). When the sea-level was lower during the early Holocene, reworking of glacial diamicton could have occurred in a coastal fringe that extended down to 20 m below present sea-level (Shaw et al., 1999). The mean depth of the demersal spawning sites was 26.4 m. It is possible that spawning now occurs on the reworked glacial sediments of the submerged littoral zone, similar to the case on Southeast Shoal (Carscadden et al., 1989).

The present study has demonstrated that the location of demersal capelin spawning sites is a function of water temperature. However, there is also a relationship with water depth. The greater the water depth of the spawning site, the greater the deviation from the mean depth of the surrounding area. This pattern suggests that the spawning sites lay in a topographic low or in depressions which become more pronounced with depth. All of the spawning sites except for the Gull Island (GI) sites were associated with gravel-filled depressions. The GI sites however, occurred in sand-filled depressions. It is possible that some of the depressions are gravel ripple troughs because half of the spawning sites were observed at depths greater than 29 m and Shaw et al. (1999) observed the ripples in 29 and 73 m water depth.

4.2.4. Conceptual model

Along the Straight Shore off the northeast coast of Newfoundland, capelin spawn both demersally and on beaches. Demersal spawning occurs on fine sand to coarse pebble sediment that ranges in size from 0.125-32 mm. In 2004, spawning occurred at temperatures that ranged between 2.4°C and 5.5°C at depths that ranged between 18 and 33 m water depth. This finding varied from the conceptual model that was initially proposed for this study in which the capelin were expected to spawn on medium sand to medium pebble substrate that ranged in size from 0.5-15 mm and at temperatures ranging between 2.0°C and 12°C in less than 50 m water depth.

The sediment size range measured was greater than suggested in the conceptual model. Fine sand was associated with spawning and non-spawning sites. The sediment at spawning sites was generally poorly-sorted sand and gravel-sized particles, whereas the sediment at the non-spawning sites was well-sorted, consisting of fine sand with minor gravel.

The temperature range at the spawning sites was narrower than suggested in the conceptual model. There was a high correlation between temperature and depth. The lowest mean spawning temperature was recorded at the deepest spawning site and the highest mean temperature at the shallowest site.

The demersal spawning sites occurred at depths that ranged between 18 m and 33 m water depth and the mean depth was 26.4 m. These depths were less than 50 m which was the depth limit proposed in the conceptual model. The depth limit of 50 m was based on the depth of the warm surface layer along the Newfoundland Shelf. The warm surface layer extends down to 0°C, which is approximately 50 m water depth. The results of this study suggest that this temperature is too cold and therefore too deep for capelin spawning on the northeast coast of Newfoundland. Temperature trends for the inshore branch of the Labrador Current on the Newfoundland Shelf from the Station 27 historical dataset show that June temperatures were similar from the 1960s through the 1990s. Surface water temperatures during these decades ranged between 5.0°C and 5.6°C, while the 2°C isotherm was at approximately 28 m water depth. Between 2000 and 2005, however, the surface temperature was 5.6°C but the 2°C isotherm deepened to 38 m. Therefore, prior to 2000, demersal spawning off the northeast coast of Newfoundland likely occurred in water depths shallower than 28 m. After 2000, demersal spawning on the northeast coast possibly occurred at depths shallower than 38 m.

The spawning sites in this study occurred in bathymetric depressions. As depth increased, the point location of the spawning sites deviated increasingly from the mean depth of the corresponding 1.0 km2 acoustic survey site. This finding suggests that the depressions became more defined with increased depth. The spawning sites were found on poorly-sorted postglacial sand and gravel at temperatures that ranged between 2.4°C and 5.5°C. The temperatures at the seabed were highly correlated with depth. The deepest site, Gull Island 1 (GI1), at 33.5 m water depth, had the coldest spawning temperature of 2.4°C. The shallowest site, Turr Island (TI), at 18 m water depth, had the warmest spawning temperature of 5.5°C. Based on the historical Station 27 temperatures, spawning may not have taken place at the GI1 site or the Wadham Island (WI) site at 32 m water depth prior to 2000.

The results of this study suggest that spawning sites are used opportunistically. While many spawning sites are reused, spawning at these sites can be delayed until such time as temperatures become appropriate (Davoren et al., 2006). In some years, capelin cease to spawn in certain locations because water temperatures are either too high or too low; therefore the capelin will proceed to seek out new spawning sites which have poorly-sorted postglacial sand and gravel sediments as well as water temperatures that promote egg and larval development (Frank et al., 1996; Templeman, 1948).

Based on the results and conclusions of this study, the conceptual model for

Straight Shore demersal capelin spawning was revised. Capelin spawning is controlled primarily by temperature (which influences the depth of spawning) and secondarily by substrate. Capelin spawn successfully at temperatures that range from 2°C to 12°C on poorly-sorted postglacial sediments that ranges in size from fine sand to coarse pebble (0.125-32 mm). The maximum depth is dependent on the 2°C isotherm which prior to 2000 was at 28 m, but since 2000 has been at 38 m. The minimum depth for spawning is 0 m (the beach).

4.3. Future directions

In the past, demersal spawning was thought to occur only when beach temperatures became too high (Templeman, 1948). The present study has demonstrated that, based on water temperatures, demersal and beach spawning can and did occur simultaneously. Since capelin spawn at many beach locations around the island of Newfoundland, it is possible that demersal spawning occurs every year at demersal locations around the island. Potential demersal spawning habitats around the island may be identified by applying the conceptual model and the supervised classification training dataset developed in this study.

Beach spawning has been reported at several circumpolar regions. The results of the present research provide a mechanism for locating potential demersal capelin spawning habitats. This mechanism may be applied to other circumpolar regions. The first step is to map out previously-glaciated locations and then to determine the temperature profile for these coastal areas in order to identify the water depths with the appropriate temperature range (approximately 2°C to 12°C) for spawning. The next step is to use the supervised classification training dataset to locate areas with sand and gravel substrate. Areas of interest may include gravel ripples which are very common in water depths less than 60 m in high wave energy environments where there is a supply of sand and gravel. Demersal capelin spawning has been described in Iceland and the Barents Sea. These two locations may be good areas to test the strength of the revised conceptual model in order to determine if it can be applied for all populations of capelin or just to the populations of capelin around Newfoundland.

This study has addressed demersal spawning in the warm surface layer above the CIL. Capelin are capable of spawning at greater depth (Saetre and Gjosaeter, 1975; Thors, 1981). The deep spawning may be occurring below the CIL in the warm bottom layer. Temperature profiles off Iceland and in the Barents Sea would need to be examined to determine if the water in these areas is stratified in the same way as the waters around Newfoundland. However, assuming that spawning in these two locations is occurring below the CIL, it is possible that demersal capelin spawning in Newfoundland occurs below the CIL as well. This possibility is another area of study that can potentially be explored with the conceptual model outlined in this study.

Newfoundland capelin move offshore to spawn in deeper water when surface water temperatures cool. In the Barents Sea capelin spawning occurs on ocean bottoms dominated by strong currents (Saetre and Gjosaeter, 1975; Stergiou, 1991). Cold periods in the Barents Sea are associated with east, north and northeast winds that blow landward and can change and decrease the intensity of the North Cape Current in the Barents Sea. This change or decrease causes a reduction in the Coriolis force acting on the current, and so, in cold years the North Cape Current could be pushed off shore (Stergiou, 1991). Stergiou (1991) suggested that when this happened, capelin spawned offshore in deeper water. During the 1990s oceanographic conditions in the Northwest Atlantic Ocean changed; capelin beach spawning in Newfoundland was delayed by as much as one month and occurred over longer periods of time (Carscadden et al., 2001; Davoren et al., 2006). From 1990 through 1993, water temperatures across the Grand Banks and Hamilton Bank were 0.5°C to 1.0°C below normal, while along the coast of Newfoundland and Labrador, water temperatures were 1°C to 3°C below normal in water depths of approximately 30 m (Colbourne et al., 1997b). Many changes to capelin biology and behaviour have been correlated with the prolonged low sea temperature in the early 1990s (Carscadden et al., 2001). When the water temperature became cooler, capelin changed their distribution patterns, leaving the Labrador coast and occupying the Grand Banks, the Flemish Cap, the and eastern Scotian Shelf (Carscadden et al., 2001; Frank et al., 1996). Despite biological changes, which included younger, and smaller spawning fish, capelin population numbers increased in the 1990s (Carscadden et al., 2001). Since capelin spawned less on beaches but populations increased, capelin were likely spawning demersally.

In the present study, the substrate associated with demersal capelin spawning was successfully identified using normal incidence acoustics and the QTC IMPACT seabed classification software. To adequately cover the seabed, multiple transect lines must be run because of the small footprint of the normal incidence system. This is a time-consuming and labour-intensive process, requiring many hours of ship time to cover a relatively small area. From the surveys carried out in this study, it is evident that regardless of whether the star or grid pattern survey design was used, there were areas that were not acoustically covered by the echo sounder. Therefore, statistics were used to make inferences about the spaces between the survey lines. The scale analysis revealed that the dimensions of the spawning sites are likely less than 1.0 km^2; so in the future, it may be more efficient to limit the surveys to 1.0 km^2. Since the area covered will be smaller, more survey lines can be done, thereby increasing the surface area covered and reducing the amount of interpretation needed to describe the seabed. The exact dimensions of the spawning beds would require additional surveying with other tools such as SCUBA, ROVs or Multibeam. Unlike normal incidence acoustic transducers which emit a single beam, Multibeam sonar emits many beams in a swath (Kenny et al., 2003) and can provide 100% coverage of the seabed, thereby eliminating the need to interpolate between the lines. Ground-truthing would be improved with the use of a grab sampler equipped with a video camera. Such a system would make it possible to retrieve physical samples of the sand and gravel substrates from the grab and simultaneously capture images of any cobble-boulder material with the video camera. Ground-truthing equipment, particularly cameras, should be connected to the ships GPS system and corrections made for the position of the camera in water.

4.4. Conclusions

This research has demonstrated that capelin demersal spawning habitat can be identified and mapped using acoustic seabed classification methods. The supervised classification training dataset developed in this study in combination with the revised conceptual model can be used to identify potential demersal capelin spawning sites around Newfoundland and other coastal areas where capelin are known to spawn on beaches but where the existence of demersal spawning has not yet been explored.

In coastal northeast Newfoundland, capelin spawn demersally as well as on beaches on poorly-sorted postglacial sand and gravel substrate in bathymetric depressions that became more pronounced with increasing depth. Spawning temperatures range between 2°C and 12°C and are correlated with depth. Demersal spawning occurred at the low end of the temperature range, while beach spawning occurred at the high end of the temperature range. The depth limit of demersal spawning depends on the depth limit of the 2°C isotherm, which was at 28 m prior to 2000 and at 38 m after 2000.

The present work has demonstrated that capelin spawning is primarily controlled by temperature and secondarily by substrate. Therefore spawning is more opportunistic than historical. While capelin may return to previously used spawning sites, spawning will only occur at those sites in successive years if water temperatures are between 2°C and 12°C which are conducive to egg and larval development. If temperatures are outside of this range, the capelin will opt for a site that offers the desired water temperatures. If water temperatures change significantly over a large area, capelin will migrate to find new areas with water temperatures that are appropriate for spawning. The identification of temperature as the primary factor controlling capelin spawning contrasts with the finding of Carscadden et al. (1989), which indicated that substrate is the controlling factor. Spawning occurs on poorly-sorted postglacial sediments that are a mixture of sand and gravel. These sediments occur both demersally and on beaches. In the case of the demersal sites, these sediments can occur at various depths, which are not always temperature-appropriate, as evidenced from the Station 27 historical temperature data.

References

Anderson, J.T., 2001. Classification of marine habitats using submersible and acoustic seabed techniques, Spatial Processes and Management of Marine Populations. Alaska Sea Grant Program, pp. 377-393.

Anderson, J.T., Gregory, R.S. and Collins, W.T., 2002. Acoustic classification of marine habitats in coastal Newfoundland. ICES Journal of Marine Science, 59: 156-167.

Anderson, J.T., Simon, J.E., Gordon, D.C. and Hurley, P.C., 2005. Linking fisheries to benthic habitats at multiple scales: Eastern Scotian Shelf haddock, American Fisheries Society Symposium, pp. 251-264.

Andrews, D.W., 2005. Beach spawning of Capelin (*Mallotus villosus*) on the northeast coast of Newfoundland. Honours Thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 31 pp.

Bell, T. and Renouf, M.A.P., 2003. Prehistoric cultures, reconstructed coasts: Maritime Archaic Indian site distribution in Newfoundland. World Archaeology, 35(3): 350-370.

Carscadden, J.E. and Frank, K.T., 2002. Temporal variability in the condition factors of Newfoundland capelin (*(Mallotus villosus)* during the past two decades. ICES Journal of Marine Science, 59: 950-958.

Carscadden, J.E., Frank, K.T. and Leggett, W.C., 2001. Ecosystem changes and the effects on capelin (*Mallotus villosus*), a major forage species. Canadian Journal of Fisheries and Aquatic Sciences, 58(1): 73-86.

Carscadden, J.E., Frank, K.T. and Miller, D.S., 1989. Capelin (*Mallotus villosus*) spawning on the Southeast Shoal: Influence of physical factors past and present. Canadian Journal of Fisheries and Aquatic Sciences, 46: 1743-1754.

Carscadden, J.E., Nakashima, B.S. and Frank, K.T., 1997. Effects of fish length and temperature on the timing of peak spawning in capelin (*Mallotus villosus*). Canadian Journal of Fisheries and Aquatic Sciences, 54: 781-787.

Carscadden, J.E. and Vilhjalmsson, H., 2002. Capelin - What are they good for? Introduction. ICES Journal of Marine Science, 59: 863-869.

Colbourne, E.B., deYoung, B., Narayanan, S. and Helbig, J., 1997a. Comparison of hydrography and circulation on the Newfoundland shelf during 1990-1993 with the long-term mean. Canadian Journal of Fisheries and Aquatic Sciences, 54(Supplemental 1): 68-80.

Colbourne, E.B., deYoung, B. and Rose, G.A., 1997b. Environmental analysis of Atlantic cod (*Gadus morhua*) migration in relation to the seasonal variations on the Northeast Newfoundland Shelf. Canadian Journal of Fisheries and Aquatic Sciences, 54(Supplimental 1): 149-157.

Collins, B., 1999. Now Quester Tangent Goes Multibeam, International Ocean Systems Design, pp. 11-14.

Collins, W., Gregory, R. and Anderson, J., 1996. A digital approach to seabed classification. Sea Technology, 37(8): 83-88.

Collins, W. and Rhynas, K.P., 1998. Acoustic seabed classification using echo sounders: Operational considerations and strategies, Proceedings of the Canadian Hydrographic Conference, Victoria, Canada, pp. 384-390.

Collins, W.T. and Lacroix, P.R., 1997. Operational philosophy of acoustic waveform data

processing for seabed classification, Proceedings of COSU '97, Singapore.
Davoren, G.K., 2004. Demersal capelin spawning sites. In: C. Rose-Taylor (Editor), St. John's, pp. Personal communication.
Davoren, G.K., Anderson, J.T. and Montevecchi, W.A., 2006. Shoal behaviour and maturity of spawning capelin (*Mallotus villosus*) off Newfoundland: demersal spawning and diel vertical movement patterns. Canadian Journal of Fisheries and Aquatic Sciences, 63: 268-284.
Davoren, G.K. and Montevecchi, W.A., 2003. Signals from seabirds indicate changing biology of capelin stocks. Marine Ecology Progress Series, 258: 253-261.
Davoren, G.K. and Montevecchi, W.A., 2005. Did signals from seabirds indicate changes in capelin biology? Reply to Carscadden (2004). Marine Ecology Progress Series, 285: 299-309.
Davoren, G.K., Montevecchi, W.A. and Anderson, J.T., 2003a. The influence of fish behaviour on search strategies of common murres (*Uria aalge*) in the northwest Atlantic. Marine Ornithology, 31: 123-131.
Davoren, G.K., Montevecchi, W.A. and Anderson, J.T., 2003b. Search strategies of a pursuit-diving marine bird and the persistence of prey patches. Ecology Monographs, 73: 463-481.
Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill Publishing Company, Austin, Texas, 182 pp.
Foster-Smith, R.L., Brown, C.J., Meadow, W.J., White, W.H. and Limpenny, D.S., 2004. Mapping seabed biotopes at two spatial scales in the eastern English Channel. Part 2. Comparison of two acoustic ground discrimination systems. Journal of the Marine Biological Association of the United Kingdom, 84: 489-500.
Frank, K.T., Carscadden, J.E. and Simon, J.E., 1996. Recent excursions of capelin *(Mallotus villosus)* to the Scotian Shelf and Flemish Cap during anomalous hydrographic conditions. Canadian Journal of Fisheries and Aquatic Sciences, 53: 1473-1486.
Freitas, R., Rodrigues, A. and Quintino, V., 2001. Classification of biosedimentry gradients: Coupling acoustic and traditional techniques, Sustainable Development International, pp. 197-202.
Freitas, R., Rodrigues, A. and Quintino, V., 2003a. Benthic biotopes remote sensing using acoustics. Journal of Experimental Marine Biology and Ecology, 285-286: 339-353.
Freitas, R. et al., 2003b. Acoustic seabed classification of marine habitats: studies in the western coastal-shelf area of Portugal. ICES Journal of Marine Science, 60: 599-608.
Hutin, E., Simard, Y. and Archambault, P., 2005. Acoustic detection of a scallop bed from a single-beam echosounder in the St. Lawrence. ICES Journal of Marine Science, 62: 966-983.
Jangaard, P.M., 1974. The Capelin (*Mallotus villosus*): Biology, distribution, exploitation, utilization, and composition. Bulletin of the Fisheries Research Board of Canada, 186: 1-70.
Kenny, A.J. et al., 2003. An overview of seabed-mapping technologies in the context of marine habitat classification. ICES Journal of Marine Science, 60: 411-418.
Nakashima, B.S. and Taggart, C.T., 2002. Is beach-spawning success for capelin,

Mallotus villosus (Muller), a function of the beach? ICES Journal of Marine Science, 59: 897-908.

Nakashima, B.S. and Wheeler, J.P., 2002. Capelin (*Mallotus villosus*) spawning behaviour in Newfoundland waters - the interaction between beach and demersal spawning. ICES Journal of Marine Science, 59: 909-916.

Pahlke, K.A., 1985. Life history and distribution of capelin, *Mallotus villosus*, in Alaskan waters. Masters Thesis, University of Alaska, Juneau, 87 pp.

Penton, P., 2006. Demersal spawning in capelin (*Mallotus villosus*) on the northeast coast of Newfoundland. Manuscript Thesis, University of Manitoba, Winnipeg, 121 pp.

Preston, J.M., Christney, A.C., Beran, L.S. and Collins, W., 2004. Statistical seabed segmentation - from images and echoes to objective clustering, Seventh European Conference on Underwater Acoustics, ECUA. Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA. Questar Tangent, Delft, The Netherlands.

Preston, J.M. and Collins, W.T., 2000. Bottom classification in very shallow water by high-speed data acquisition, Oceans 2000 MTSIIEEE Conference Proceedings.

Prinsenberg, S.J., Peterson, I.K., Narayanan, S. and Umoh, J.U., 1997. Interaction between atmosphere, ice cover, and ocean off Labrador and Newfoundland from 1962 to 1992. Canadian Journal of Fisheries and Aquatic Sciences, 54(Supplemental 1): 30-39.

Prothero, D.R. and Schwab, F., 1997. Sedimentary Geology: An Introduction to Sedimentary Rocks and Stratigraphy. W.H. Freeman and Company, New York, 575 pp.

Quester Tangent Corporation, 2004. QTC IMPACT ™. Acoustic Seabed Classification for Echo Sounders. Quester Tangent Corporation, Marine Technology Centre, Sidney, British Columbia, Canada.

Rose, G.A., 1993. Cod spawning on a migration highway in the north-west Atlantic. Nature, 366: 458-461.

Saetre, R. and Gjosaeter, J., 1975. Ecological investigations on the spawning grounds of the Barents Sea capelin. Fiskerdirektoratets-Skrifter-Serie-Havundersokelser, 16: 203-227.

SAS, 2000. Statistical Analysis System. SAS Institute Inc., Cary, North Carolina.

Shackell, N.L., Carscadden, J.E. and Miller, D.S., 1994a. Migration of pre-spawning capelin (*Mallotus villosus*) to temperature on the northern Grand Bank, Newfoundland. ICES Journal of Marine Science, 51: 107-114.

Shackell, N.L., Shelton, P., Hoeing, J.M. and Carscadden, J.E., 1994b. Age- and sex-specific survival of northern Grand Bank capelin (*Mallotus villosus*). Canadian Journal of Fisheries and Aquatic Sciences, 51: 642-649.

Shaw, J. and Edwardson, K.A., 1994. Surficial sediments and post-glacial relative sea-level history, Hamilton Sound, Newfoundland. Atlantic Geology, 30(2): 97-112.

Shaw, J., Forbes, D.L. and Edwardson, K.A., 1999. Surficial sediments and placer gold on the inner shelf and coast of Northeast Newfoundland. Geological Survey of Canada Bulletin, 532: 76-96.

Stergiou, K.I., 1991. Possible Implications of climate variability on the presence of capelin (*Mallotus villosus*) off the Norwegian coast. Climate Change, 19: 369-391.

Templeman, W., 1948. The life history of the capelin (*Mallotus villosus* O.F. Muller) in Newfoundland waters. Bulletin of the Newfoundland Gouvernment Laboratory, 17: 1-151.

Thors, K., 1981. Environmental features of the capelin spawning grounds south of Iceland. Rit Fiskideildar, 6: 7-13.

Vilhjalmsson, H., 1994. The Icelandic Capelin Stock: Capelin, *Mallotus villosus* (Muller) in the Iceland-Greenland-Jan Mayen area. Rit Fiskideildar, 13: 1-281.

von Szalay, P.G. and McConnaughey, R.A., 2002. The effect of slope and vessel speed on the performance of a single beam acoustic seabed classification system. Fisheries Research, 54: 181-194.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology, 30: 377-392.

Wienberg, C. and Bartholoma, A., 2005. Acoustic seabed classification in a coastal environment (outer Weser Estuary, German Bight) - a new approach to monitor dredging and dredge spoil disposal. Continental Shelf Research, 25: 1143-1156.

Appendices

Appendix 1: Statistical measures and substrate descriptions of the Cracker's Rock (CR) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
CR - grab 1	-3	-2.5	-2.3	-2	-1.5	-1.2	-0.5	-2 -1	-2	granule	-1.9	granule	0.7	moderately well-sorted	0.22	fine-skewed	1.28	leptokurtic	granule, pebble gravel
CR - grab 2	-3.7	-3.2	-2.9	-2.3	-1.8	-1.5	-1	-2	-2.3	pebble	-2.33	pebble	0.83	moderately-sorted	-0.05	symmetrical	1.01	mesokurtic	granule, pebble gravel

Appendix 2: Statistical measures and substrate descriptions of the Deadman's Bay 1 (DB1) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
DB 1 - grab 1	-4.7	-4.05	-3.2	-2.25	-1.5	-1.35	-0.8	-1	-2.25	pebble	-2.55	pebble	1.27	poorly-sorted	-0.29	coarse skewed	0.94	mesokurtic	pebble gravel and granule
DB 1 - grab 2	n/a	n/a	n/a	-4.7	-3.1	-1.8	-0.55	-5	-4.7	pebble	-2.17	pebble	-0.53	very well-sorted	-10.16	strongly skewed toward coarse particles	0.07	very platykurtic	medium to coarse pebble with minor granules and very coarse sand
DB 1 - grab 3	n/a	-4.6	-3.95	-3.05	-1.8	-1.1	-0.4	-1	-3.05	pebble	-2.92	pebble	0.81	moderately-sorted	-7.07	strongly skewed toward coarse particles	-0.08	very platykurtic	medium pebble gravel with granule and coarse sand
DB 1 - grab 4	-4.35	-3.3	-3.1	-1.8	-0.8	-0.2	0.2	-3 -1 0	-1.8	granule	-1.77	granule	1.46	poorly-sorted	-0.04	symmetrical	0.81	platykurtic	granule to medium pebble gravel with coarse to very coarse sand
DB 1 - grab 5	-3.95	-1.4	-1	-0.8	-0.4	-0.2	0.05	0	-0.8	very coarse sand	-0.8	very coarse sand	0.91	moderately-sorted	-0.29	coarse skewed	2.73	very leptokurtic	coarse to very coarse sand with minor granule and pebbles

Appendix 3: Statistical measures and substrate descriptions of the Deadman's Bay 2 (DB2) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
DB 2 - grab 1	-4.5	-3.8	-3.2	-1.4	-0.7	-0.35	0.05	0	-1.4	granule	-1.85	granule	1.55	poorly-sorted	-0.38	strongly coarse skewed	0.75	platykurtic	granule to medium pebble gravel and very coarse sand
DB 2 - grab 2	-4.8	-4.4	-4	-0.7	0	0.05	0.15	-4 0	-0.7	very coarse sand	-1.68	granule	1.86	poorly-sorted	-0.66	strongly coarse skewed	0.51	very platykurtic	medium pebble gravel and coarse to very coarse sand
DB 2 - grab 3	n/a	-4.6	-3.8	-3	-1.8	-1.4	-0.8	-1	-3	pebble	-3	pebble	0.68	moderately well-sorted	-3.25	strongly coarse skewed	-0.16	very platykurtic	pebble gravel with granules and very coarse sand
DB 2 - grab 4	-4.3	-3.75	-3.2	-1.5	0	0.2	1	-1	-1.5	granule	-1.68	granule	1.79	poorly-sorted	-0.1	strongly coarse skewed	0.68	platykurtic	coarse sand to medium pebble gravel

Appendix 4: Statistical measures and substrate descriptions of the Gull Island 1 (GI1) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
GI 1 - grab 1	-4.5	-3.85	-3.5	-0.2	0.7	1	1.7	-3.5 0.5	-0.2	very coarse sand	-1.02	Granule	2.15	very poorly-sorted	-0.45	strongly coarse skewed	0.6	very platykurtic	medium pebble to coarse sand
GI 1 - grab 2	-3.6	-0.9	0	0.4	1.2	1.5	2	0.5 2	0.4	coarse sand	0.33	coarse sand	1.45	poorly-sorted	-0.26	coarse skewed	1.91	very leptokurtic	coarse to medium sand with minor pebbles
GI 1 - grab 3	0	0.3	0.6	1	1.5	1.8	2.1	2	1	coarse sand	1.03	medium sand	0.69	moderately well-sorted	0.06	symmetrical	0.96	mesokurtic	medium to coarse sand
GI 1 - grab 4	-0.2	0.15	0.25	0.8	1.2	1.45	2	0.5 2	0.8	coarse sand	0.8	coarse sand	0.66	moderately well-sorted	0.05	symmetrical	0.95	mesokurtic	medium to coarse sand
GI 1 - grab 5	-1.05	0	0.1	0.5	1	1.2	1.9	0.5	0.5	coarse sand	0.57	coarse sand	0.75	moderately-sorted	0.06	symmetrical	1.34	leptokurtic	medium to coarse sand
GI 1 - grab 6	-3.1	-1.4	-1	-0.7	-0.2	-0.1	0.1	0	-0.7	very coarse sand	-0.73	very coarse sand	0.81	moderately-sorted	-0.29	coarse skewed	1.64	very leptokurtic	very coarse sand with minor pebbles
GI 1 - grab 7	-3	-1.4	-1	-0.3	0.1	0.2	0.6	0	-0.3	very coarse sand	-0.5	very coarse sand	0.95	moderately-sorted	-0.44	strongly coarse skewed	1.34	leptokurtic	coarse to very coarse sand with minor pebbles
GI 1 - grab 8	-2.1	-1.3	-1	-0.3	0.2	0.5	0.8	0	-0.3	very coarse sand	-0.37	very coarse sand	0.89	moderately-sorted	-0.18	coarse skewed	0.99	mesokurtic	coarse to very coarse sand with pebbles

Appendix 5: Statistical measures and substrate descriptions of the Gull Island 2 (GI2) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
GI 2 - grab 1	-1.85	-1.6	-1.3	-0.8	-1.4	-0.2	0.1	0	-0.8	very coarse sand	-0.87	very coarse sand	0.65	moderately well-sorted	-0.11	coarse skewed	-7.99	very platykurtic	very coarse sand and granules
GI 2 - grab 2	0.9	1.5	1.75	2.05	2.2	2.3	2.55	2.74	2.05	fine sand	1.95	medium sand	0.45	well-sorted	-0.38	strongly coarse skewed	1.5	leptokurtic	medium to fine sand
GI 2 - grab 3	-1.8	-1.2	-0.9	-0.5	-0.1	0	0.9	0	-0.5	very coarse sand	-0.57	very coarse sand	0.71	moderately well-sorted	-0.06	symmetrical	1.38	leptokurtic	granules and very coarse sand
GI 2 - grab 4	-1.7	-1.2	-1.1	-0.8	-0.3	-0.1	0.2	0.5 2	-0.8	very coarse sand	-0.7	very coarse sand	0.56	moderately well-sorted	0.16	fine skewed	0.97	mesokurtic	very coarse sand with granules
GI 2 - grab 5	-3.8	-3.2	-2.85	-1.9	-1.4	-1.1	-0.2	-1	-1.9	granule	-2.07	pebble	1.07	poorly-sorted	-0.15	coarse skewed	1.02	mesokurtic	medium pebble and granule gravel with traces of very coarse sand
GI 2 - grab 6	-1.5	-0.9	-0.8	-0.4	-0.1	0	0.3	0	-0.4	very coarse sand	-0.43	very coarse sand	0.5	moderately well-sorted	-0.17	coarse skewed	1.05	mesokurtic	coarse to very coarse sand with minor granules
GI 2 - grab 7	n/a	n/a	n/a	-4.2	-0.9	-0.4	0.05	-5 0	-4.2	pebble	-1.53	granule	-0.09	very well-sorted	74.5	strongly fine skewed	-0.02	very platykurtic	medium pebbles with very coarse sand
GI 2 - grab 8	-2.9	-2.7	-2.4	-2.15	-1.8	-1.5	-1.05	-2	-2.15	pebble	-2.12	pebble	0.58	moderately well-sorted	0.14	fine skewed	1.26	leptokurtic	granule pebble gravel
GI 2 - grab 9	-2.8	-2.5	-2.4	-2.1	-1.8	-1.5	-1.1	-2	-2.1	pebble	-2.03	pebble	0.51	moderately well-sorted	0.19	fine skewed	1.16	leptokurtic	granule pebble gravel

Appendix 6: Statistical measures and substrate descriptions of the Hincks Rock (HR) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
HR - grab 1	-2.1	-1.85	-1.7	-1.15	-0.7	-0.3	0.3	-1	-1.15	granule	-1.05	granule	0.71	moderately well-sorted	0.21	fine skewed	0.98	mesokurtic	granules with very coarse sand
HR - grab 2	-1.8	-1.5	-1.3	-1	-0.5	-0.25	0.4	-1	-1	granule	-0.92	very coarse sand	0.65	moderately well-sorted	0.24	fine skewed	1.13	leptokurtic	granules with very coarse san

Appendix 7: Statistical measures and substrate descriptions of the Turr Island (TI) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
TI - grab 1	-3.4	-2.9	-2.5	-1.9	-1.1	-0.9	-0.2	-2 -1	-1.9	granule	-1.9	granule	0.98	moderately-sorted	0.03	symmetrical	0.94	mesokurtic	pebbles to coarse sand
TI - grab 2	-3.75	-2.95	-2.5	-1.5	-0.75	-0.15	0.6	-1	-1.5	granule	-1.53	granule	1.36	poorly-sorted	-0.04	symmetrical	1.02	mesokurtic	Pebbly coarse sand

Appendix 8: Statistical measures and substrate descriptions of the Wadham Islands (WI) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
WI - grab 1	-3.8	-3.2	-2.2	-1	0	0.2	0.9	-1 0	-1	very coarse sand	-1.33	granule	1.56	Poorly-sorted	-0.24	coarse skewed	0.88	platykurtic	coarse sand to pebble
WI - grab 2	-1.85	-0.95	-0.75	-0.25	0.5	0.1	0.35	0	-0.25	very coarse sand	-0.37	very coarse sand	0.6	moderately well-sorted	-0.39	strongly coarse skewed	0.72	platykurtic	coarse to very coarse sand
WI - grab 3	n/a	n/a	-5	-1.7	-0.8	-0.4	0.05	-5 0	-1.7	granule	-0.7	very coarse sand	-0.09	very well-sorted	30.75	strongly fine skewed	0	very platykurtic	coarse to very coarse sandy pebble gravel
WI - grab 4	-0.25	0.1	0.25	0.7	1.1	1.4	1.95	0.5 2	0.7	coarse sand	0.73	coarse sand	0.66	moderately well-sorted	0.11	fine skewed	1.06	mesokurtic	medium to coarse sand
WI - grab 5	-1.8	-1.05	-0.95	-0.7	-0.2	-0.1	0.1	0	-0.7	very coarse sand	-0.62	very coarse sand	0.53	moderately well-sorted	0.05	symmetrical	1.04	mesokurtic	very coarse sand to granule

Appendix 9: Statistical measures and substrate descriptions of the Wesleyville (WV) demersal spawning site based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
WV - grab 1	1.2	2.8	2.85	2.9	2.95	2.95	3	3	2.9	fine sand	2.88	Fine sand	0.31	very well-sorted	-0.61	strongly coarse skewed	7.38	very leptokurtic	fine sand with minor medium sand
WV - grab 2	1.2	2.8	2.85	2.9	2.95	2.95	3	3	2.9	fine sand	2.88	Fine sand	0.31	very well-sorted	-0.61	strongly coarse skewed	7.38	very leptokurtic	fine sand with minor medium sand
WV - grab 3	2.8	2.85	2.85	2.9	2.9	2.95	3	3	2.9	fine sand	2.9	Fine sand	0.06	very well-sorted	0	symmetrical	1.64	very leptokurtic	fine sand
WV - grab 4	2.8	2.8	2.85	2.9	2.95	2.95	3	3	2.9	fine sand	2.88	Fine sand	0.07	very well-sorted	-0.17	coarse skewed	0.82	platykurtic	fine sand
WV - grab 5	2.8	2.85	2.85	2.9	2.95	3	3	3	2.9	fine sand	2.92	Fine sand	0.07	very well-sorted	0.17	fine skewed	0.82	platykurtic	fine sand
WV - grab 6	2.8	2.8	2.85	2.9	2.95	2.95	3	3	2.9	fine sand	2.88	Fine sand	0.07	very well-sorted	-0.17	coarse skewed	0.82	platykurtic	fine sand
WV - grab 7	-0.3	2.3	2.8	2.85	2.95	2.95	3	3	2.85	fine sand	2.7	Fine sand	0.66	moderately well-sorted	-0.8	strongly coarse skewed	9.02	very leptokurtic	fine sand with minor very coarse sand
WV - grab 8	-3.95	0.2	2	2.2	2.5	2.6	2.8	2.74	2.2	fine sand	1.67	Medium sand	1.62	poorly-sorted	-0.74	strongly coarse skewed	5.53	very leptokurtic	fine sand with minor pebbles
WV - grab 9	-1.1	2	2.05	2.25	2.6	2.7	2.8	2.74	2.25	fine sand	2.32	Fine sand	0.77	moderately-sorted	-0.22	coarse skewed	2.91	very leptokurtic	fine sand with minor granules
WV - grab 10	-4.8	-3.8	-2	2	2.4	2.6	2.8	2.74	2	fine sand	0.27	Coarse sand	2.75	very poorly-sorted	-0.8	strongly coarse skewed	0.71	platykurtic	fine sand with pebbles
WV - grab 11	-1.8	2	2.05	2.2	2.5	2.75	2.8	2.74	2.2	fine sand	2.32	Fine sand	0.88	moderately-sorted	-0.14	coarse skewed	4.19	very leptokurtic	fine sand with minor granules

Appendix 10: Statistical measures and substrate descriptions of the Capelin Cove (CC) spawning beach based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
CC - grab 1	n/a	n/a	-4.85	-3.5	-0.5	0.1	0.7	-4.98	-3.5	pebble	-1.13	granule	0.13	very well-sorted	41	strongly fine-skewed	0.07	platykurtic	coarse sandy pebble gravel
CC - grab 2	n/a	n/a	-4.65	-3.6	-0.1	0.6	1.1	-4.98	-3.6	pebble	-1	granule	0.32	very well-sorted	10.27	strongly fine-skewed	0.1	platykurtic	coarse sandy pebble gravel
CC - grab 3	n/a	-4.6	-4.25	-2.85	-0.45	0.45	1	-2	-2.9	pebble	-2.33	pebble	1.41	poorly-sorted	3.5	strongly fine-skewed	0.11	platykurtic	coarse sandy pebble gravel
CC - grab 4	n/a	-3.55	-2.45	-0.9	-0.2	0.1	0.7	0	-0.9	very coarse sand	-1.45	granule	1.02	poorly-sorted	1.56	strongly fine-skewed	0.13	platykurtic	coarse sand to medium pebble gravel
CC - grab 5	n/a	-3.8	-2.55	-0.7	0.3	0.5	0.8	-0.49	-0.7	very coarse sand	-1.33	granule	1.2	poorly-sorted	1.15	strongly fine-skewed	0.12	platykurtic	coarse sand to medium pebble gravel
CC - grab 6	n/a	n/a	-4.2	-1.7	0	0.3	0.8	0	-1.7	granule	-0.47	very coarse sand	0.2	very well-sorted	8.79	strongly fine-skewed	0.08	platykurtic	coarse sand to medium pebble gravel
CC - grab 7	n/a	-3.8	-3.4	-2.2	-0.7	-0.2	0.45	-2	-2.2	pebble	-2.07	pebble	0.97	moderately-sorted	5.44	strongly fine-skewed	0.07	platykurtic	coarse sand to medium pebble gravel
CC - grab 8	n/a	-3.3	-2.75	-1.1	0.25	0.55	0.8	-2	-1.1	granule	-1.28	granule	1.08	poorly-sorted	1.8	strongly fine-skewed	0.11	platykurtic	coarse sand to medium pebble gravel

Appendix 11: Statistical measures and substrate descriptions of the Lumsden (LD) spawning beach based on grain-size analysis using phi (Φ) unit values from histograms and probability plots.

Sample No.	Φ5	Φ16	Φ25	Φ50	Φ75	Φ84	Φ95	Mode Φ	Median Φ		Mean Φ		Sorting Φ		Skewness		Kurtosis		Description
LD - grab 1	-3.6	-3.2	-2.9	-2.2	-1.35	-0.85	0.15	-2	-2.2	pebble	-2.08	pebble	1.16	poorly-sorted	0.2	fine-skewed	0.99	mesokurtic	very coarse sand to medium pebble
LD - grab 2	-3.9	-3.35	-2.75	-1.65	0	0.55	1.3	-2	-1.65	granule	-1.48	granule	1.76	poorly-sorted	0.13	fine-skewed	0.77	platykurtic	coarse sandy pebble gravel
LD - grab 3	n/a	n/a	-2	-1.2	-0.7	-0.45	0	0	-1.2	granule	-0.55	very coarse sand	-0.11	very well-sorted	n/a	n/a	0	platykurtic	very coarse sand and granules
LD - grab 4	-3.1	-2.55	-2.2	-1.5	-0.7	-0.3	0.45	-1	-1.5	granule	-1.45	granule	1.1	poorly-sorted	0.08	symmetrical	0.97	mesokurtic	very coarse sand to pebble gravel
LD - grab 5	-3.3	-2.7	-2.3	-1.1	0	0.2	0.6	0	-1.1	granule	-1.2	granule	1.32	poorly-sorted	-0.12	coarse-skewed	0.69	platykurtic	coarse sand to pebble gravel
LD - grab 6	-3	-2.4	-2.1	-1.65	-1.2	-1	-0.45	-1	-1.65	granule	-1.68	granule	0.74	moderately-sorted	-0.07	symmetrical	1.16	leptokurtic	granule and pebble gravel
LD - grab 7	-4.1	-2.9	-2.6	-1.9	-1.2	-0.8	0	-1	-1.9	granule	-1.87	granule	1.15	poorly-sorted	-0.01	symmetrical	1.2	leptokurtic	granule and pebble gravel

Appendix 12: QTC IMPACT unsupervised classification statistics for the Cracker's Rock dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi2$	Score
0	3589.9	-	1	1158	3.1	3590
1	1462.58	2.38	1	498	1.22	670
			2	660	1.3	856
2	**941.29**	**5.58**	**1**	**80**	**0.55**	**44**
			2	**685**	**0.96**	**630**
			3	**420**	**0.64**	**268**
3	982.5	9.53	1	89	0.74	66
			2	637	0.9	576
			3	392	0.76	296
			4	40	1.11	45

Appendix 13: QTC IMPACT unsupervised classification statistics for the Deadman's Bay dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi2$	Score
0	1807.77	-	1	1162	1.56	1808
1	1549.61	2.29	1	112	0.73	81
			2	1050	1.4	1468
2	**1017.49**	**9.5**	**1**	**91**	**1.08**	**98**
			2	**407**	**0.79**	**321**
			3	**664**	**0.9**	**599**
3	919.24	17.03	1	109	0.93	101
			2	323	1.07	346
			3	228	0.66	150
			4	502	0.64	322
4	870.48	23.4	1	109	0.93	101
			2	208	1.17	243
			3	258	0.71	182
			4	486	0.51	250
			5	101	0.93	94
5	890.7	52.77	1	58	0.62	36
			2	207	1.2	249
			3	260	0.65	168
			4	477	0.61	292
			5	101	0.93	94
			6	59	0.88	52

Appendix 14: QTC IMPACT unsupervised classification statistics for the Gull Island dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	χ2	Score
0	166683.08	-	1	8770	19.01	166683
1	24451	2.74	1	4601	4.03	18556
			2	4169	1.41	5895
2	**13233.15**	**9.77**	**1**	**2818**	**1.01**	**2855**
			2	**2488**	**2.62**	**6511**
			3	**3464**	**1.12**	**3868**
3	15106.37	23.72	1	2841	0.95	2712
			2	2277	2.29	5219
			3	3440	1.99	6834
			4	212	1.61	342

Appendix 15: QTC IMPACT unsupervised classification statistics for the Hincks Rock dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	χ2	Score
0	47801.68	-	1	3698	12.93	47802
1	6913.12	2.04	1	2076	1.89	3914
			2	1622	1.85	2999
2	**5591.63**	**4.86**	**1**	**356**	**1.27**	**451**
			2	**1591**	**2.36**	**3750**
			3	**1751**	**0.79**	**1390**
3	5890.6	9.09	1	367	1.47	539
			2	1397	2.45	3419
			3	1269	0.78	996
			4	665	1.41	939

Appendix 16: QTC IMPACT unsupervised classification statistics for the North Penguin Island dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi 2$	Score
0	2621	-	1	1110	2.36	2621
1	1522.65	3.12	1	147	1.58	232
			2	963	1.34	1291
2	**1311.16**	**6.65**	**1**	**167**	**1.66**	**278**
			2	**901**	**1.11**	**1004**
			3	**42**	**0.69**	**29**
3	1311.16	12.93	1	165	1.6	264
			2	886	0.98	872
			3	8	0.98	8
			4	51	0.41	21
4	1032.83	34.96	1	28	0.71	20
			2	883	1	879
			3	8	0.98	8
			4	50	0.61	31
			5	141	0.68	96

Appendix 17: QTC IMPACT unsupervised classification statistics for the Turr Island dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi 2$	Score
0	5534.99	-	1	1094	5.06	5535
1	1940.06	2.5	1	281	3.46	972
			2	813	1.19	968
2	**1059.55**	**8.56**	**1**	**125**	**0.89**	**112**
			2	**798**	**0.7**	**558**
			3	**171**	**2.28**	**390**
3	934.14	15.62	1	37	0.6	22
			2	799	0.71	564
			3	162	1.43	232
			4	96	1.22	117
4	884.34	26.08	1	37	0.6	22
			2	798	0.71	564
			3	138	1.19	164
			4	96	1.22	117
			5	25	0.73	18
5	812.06	53.05	1	38	0.78	30
			2	799	0.65	519
			3	138	1.19	164
			4	41	1.39	57
			5	25	0.73	18
			6	53	0.46	24

Appendix 18: QTC IMPACT unsupervised classification statistics for the Wadham Islands dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi 2$	Score
0	**27637.35**	**-**	**1**	**8548**	**3.32**	**27637**
1	28699.68	2.81	1	629	1.83	1153
			2	7919	3.48	27547

Appendix 19: QTC IMPACT unsupervised classification statistics for the Wesleyville dataset. Optimal split level in bold.

Split	Total Score	CPI	Class	Members	$\chi 2$	Score
0	142582.38	-	1	6125	23.28	14582
1	**31082.36**	**2.44**	**1**	**1283**	**3.01**	**3862**
			2	**4842**	**5.62**	**27220**
2	27382.63	7.29	1	1044	1.83	1905
			2	1570	3.7	5810
			3	3511	5.6	19667
3	18540.52	20.79	1	927	2.76	2563
			2	953	3.18	2031
			3	2128	2.48	5268
			4	2117	3.63	7679
4	14370.57	62.03	1	916	2.86	2619
			2	988	2.97	2931
			3	2088	2.64	5518
			4	1701	1.78	3028
			5	432	0.64	275
5	11517.23	139.76	1	557	1.17	654
			2	1019	1.87	1904
			3	2061	2.42	4991
			4	1700	1.82	3093
			5	434	0.65	281
			6	354	1.68	595