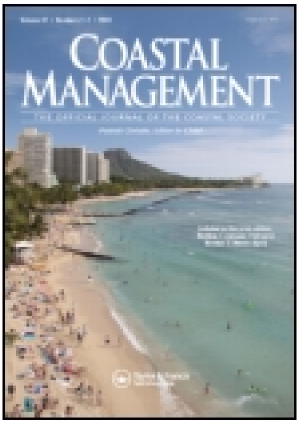

Coastal Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ucmg20

The British Columbia marine ecosystem classification: Rationale, development, and verification

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Available online: 30 Sep 2008

To cite this article: Mark A. Zacharias, Don E. Howes, John R. Harper & Peter Wainwright (1998): The British Columbia marine ecosystem classification: Rationale, development, and verification, Coastal Management, 26:2, 105-124

To link to this article: http://dx.doi.org/10.1080/08920759809362347

The British Columbia Marine Ecosystem Classification: Rationale, Development, and Verification

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There is an increasing need to develop new tools and techniques for marine conservation, resource management, and planning. One of these new techniques is the application of terrestrial ecosystem approaches to the development of an equivalent marine methodology. These modified ecosystem approaches have been used in the development of the British Columbia Marine Ecosystem Classification (BCMEC) for the Pacific coast of Canada. The classification is hierarchical, and consists of four nested divisions based on physical properties and a fifth division based on current, depth, bottom substrate, bottom relief, and wave exposure. The fifth division—termed ecounits*—was created at a considerably larger scale (1:250,000), and is the first example of a large-scale marine classification applied over a large area (453,000 km^2). The ecounits were developed to evaluate the boundaries and homogeneity of the four larger divisions, as well as for the application to coastal management and marine protected areas planning. This article presents the development of the ecounits, and their application toward evaluating the boundaries of the other divisions. Results indicate that large-scale ecosystem classifications can be used as a tool in coastal management and protected areas planning. The utility of the ecounits will increase as additional physical and oceanographic properties (i.e., salinity and temperature) are incorporated.*

Keywords ecosystem classification, gap analysis, marine mapping, marine protected areas, Northeast Pacific

Experience in terrestrial environments has demonstrated that the management, conservation, and preservation of individual species is difficult from both ecological and political standpoints (Edwards, 1996; Scott et al., 1993). Species based approaches as a means for conservation have been criticized for several reasons, including their inability to

Received 22 May 1997; accepted 5 December 1997.

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Coastal Management, 26:105–124, 1998

0892-0753/98 $12.00 + .00

address species of concern in a timely manner, their expense, and their bias toward "charismatic megafauna" (Jennings, 1995; Scott et al., 1993).

In response to these concerns, a number of inventory and analysis tools have been developed for the conservation of ecosystems (Cherrill et al., 1995; Conroy & Noon, 1996; Edwards, 1996; Jennings, 1995; Merrill, Wright, & Scott, 1995; Scott et al., 1993). These tools are collectively known as "ecosystem approaches," and include ecosystem classification, landscape ecology, and gap analysis (Caicco et al., 1995; Davis & Reiners, 1996; Short & Hestbeck, 1995). Ecosystem approaches are implemented by mapping biological and physical data over large areas to identify "representative" and "distinct" areas, as well as gaps in the habitat ranges of species of concern so that mitigation strategies for their conservation can be developed (Scott et al., 1993).

Although the ecosystem approach has been accepted as part of the terrestrial conservation ethic, there has been less effort at developing methodologies to supplement the single species approach in marine systems (Brunckhorst & Bridgewater, 1995; Canada, 1994; Cowardin et al., 1979; Davis, 1995; Dethier, 1992; Harding & Hirvonen, 1996; Harper et al., 1993; Howe, Zacharias, & Harper, 1996; Ray, 1976; Salm & Clarke, 1984; Taylor & Roff, 1997). This deficiency was recognized as early as the 1950s, and many authors predicted the worldwide collapse of fisheries as a result of an inadequate understanding of population ecology, food webs, and habitat requirements (Carson, 1963; Hardin, 1966; Ray, 1976). The lack of an ecosystem approach for marine conservation more recently has been noted by Norse (1993), Thorne-Miller and Catena (1991), and the National Research Council (1995). These authors concluded that traditional approaches to marine conservation often are inadequate, and that new techniques—including ecosystem approaches—must be developed (National Research Council, 1995; Norse, 1993; Thorne-Miller & Catena, 1991).

There has been progress into the development of marine ecosystem classifications in recent years, but these endeavors still lag behind terrestrial efforts (Brunckhorst & Bridgewater, 1995; Canada, 1994; Cowardin et al., 1979; Dethier, 1992; Harding & Hirvonen, 1996; Harper et al., 1993; Howes, Zacharias, & Harper, 1996; Ray, 1976; Salm & Clarke, 1984; Taylor & Roff, 1997). This article discusses the application of an ecosystem based approach to the development of the British Columbia Marine Ecosystem Classification (BCMEC). The BCMEC was designed to assist in conservation, resource management, and coastal planning. The classification is hierarchical in nature, and consists of four nested divisions based on physical properties mapped at a 1:2,000,000 scale. Also included is a fifth division—termed *ecounits*—based on the physical characteristics of current, depth, bottom substrate, bottom relief, and wave exposure. The ecounits were developed to evaluate the boundaries and homogeneity of the larger ecosections, as well as for the application toward coastal management and marine protected areas planning. The ecounits were created at a considerably larger scale (1:250,000), and are the first example of a large-scale marine classification applied over a large area (453,000 km^2). This article presents the development of the ecounits, and their application toward evaluating the boundaries of the other divisions.

Methods

The British Columbia Marine Ecosystem Classification

The larger divisions of the BCMEC were based on the *Classification of the Marine Regions of Canada,* and developed from the systematic application of physical criteria deemed significant in controlling regional ecological processes (Harding & Hirvonen, 1996; Harper et al., 1993; Hirvonen, Harding, & Landucci, 1995). Four levels of criteria were applied to define "ecozones" (ice regimes and ocean basins), "ecoprovinces" (ocean regimes and continental margins), "ecoregions" (marginal seas), and "ecosections" (mixing and stratification) (Harper et al., 1993; Hirvonen, Harding, & Landucci, 1995). This original classification was modified to include additional ecosections, and adjust the ecoprovince and ecoregion boundaries to integrate with the British Columbia Terrestrial Ecosystem Classification. The Pacific coast is comprised of a single ecozone, 3 ecoprovinces, 5 ecoregions, and 12 ecosections (Table 1; Figure 1). These four divisions were mapped at a 1:2,000,000 scale, and the physiographic, oceanographic, and biological rationale for each ecosection are reviewed in Table 2.

There are, however, some limitations to the BCMEC. The ecosection level of the classification is comprised of only 12 areas, which often are too large for use in coastal management and marine protected areas planning. In addition, while the ecosections were generated using a combination of expert opinion and limited data sets, there was no method of verifying the representativeness of the ecosections and the accuracy of their boundaries.

To address these deficiencies, the ecounit hierarchy of the BCMEC was created to further delineate the marine environment into homogenous regions, and evaluate the boundaries of the larger ecosections.

Selecting Data to Create the Ecounits

The ecounit hierarchy differs from the larger divisions in the BCMEC in that it is composed solely of empirical data collected in a systematic fashion, as opposed to the expert knowledge and consensus based approach used to delineate the other divisions (Harper et al., 1993). The methodology used to create the ecounits resembles terrestrial approaches

Table 1
The British Columbia Marine Ecosystem Classification

Ecozones	Ecoprovinces	Ecoregions	Ecosections	Ecosection area (km^2)
Pacific	North Pacific	Subarctic Pacific	Subarctic Pacific	170,980
		Transitional Pacific	Transitional Pacific	148,500
	Pacific Shelf and Mountains	Outer Pacific Marine Shelf	Continental Slope	33,300
			Vancouver Island Shelf	16,700
			Queen Charlotte Sound	36,390
			Dixon Entrance	10,890
			Hecate Stait	12,800
		Inner Pacific Marine Shelf	North Coast Fjords	9,600
			Queen Charlotte Strait	2,300
			Johnstone Strait	2,500
	Georgia-Puget Basin	Georgia Basin	Juan de Fuca Strait	1,500
			Strait of Georgia	7,900

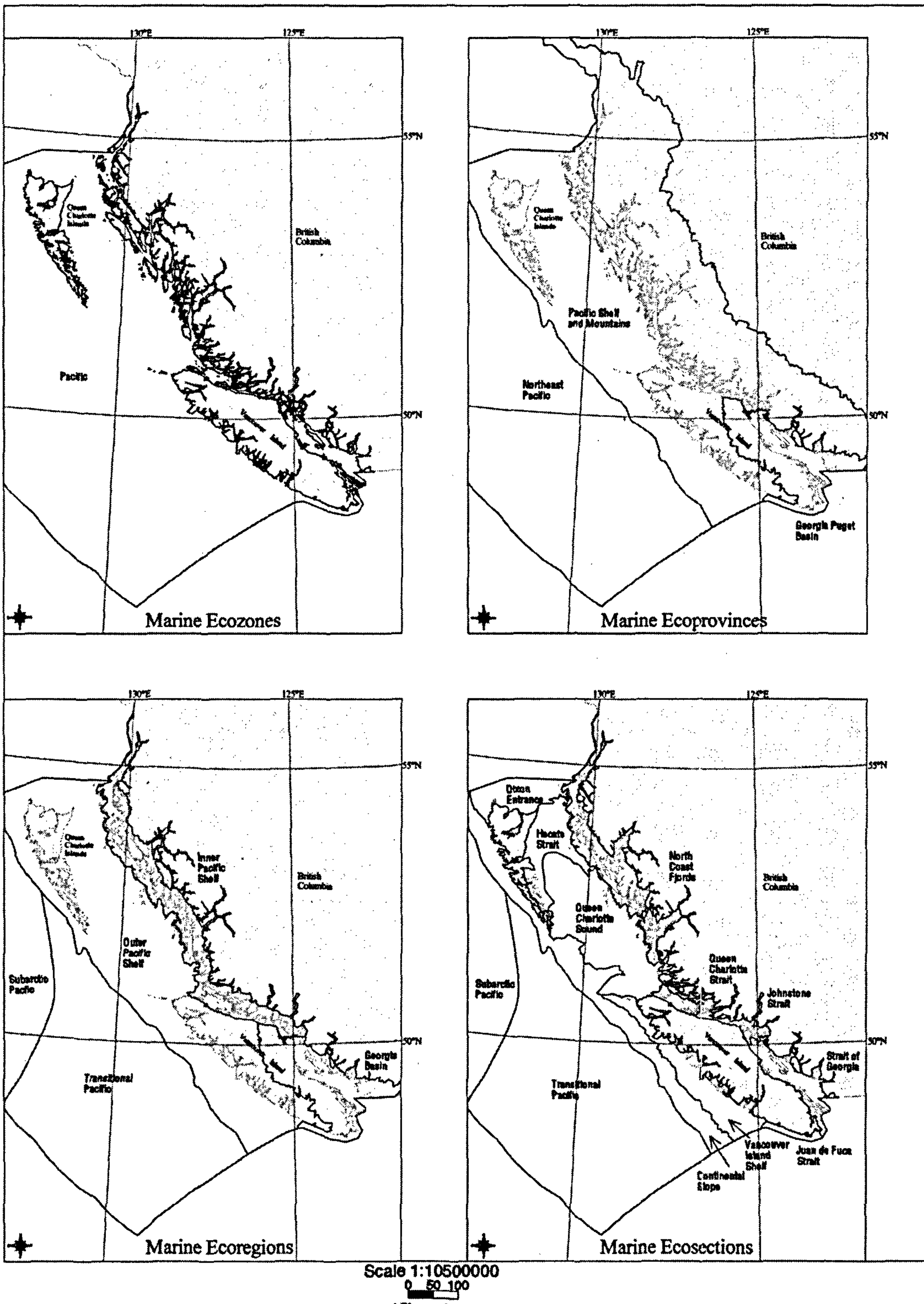

Figure 1. The Pacific marine ecozone, ecoregions, ecoprovinces, and ecosections of British Columbia.

Table 2
Pacific marine ecosections and their justification criterion

Marine ecosections	Physiographic features	Oceanographic features	Biological features	Boundary rationale
Johnstone Strait	Narrow, constricted channels	Protected coastal waters with strong currents; well mixed, poorly stratified	Migratory corridor for anadromous fish; rich sessile, hard substrate invertebrate community; diverse species assemblage of benthic fish	Johnstone Strait has greater mixing and more channels than areas to south; Queen Charlotte Strait is more marine
Continental Slope	Steep sloping shelf	Strong across slope and downslope turbidity currents	Upwelling zone; productive coastal plankton communities and unique assemblages of benthic species	Transitional area between continental slope and abyssal plane
Dixon Entrance	Across-shelf trough with depths mostly <300 m; surrounded by low lying coastal plains (Hecate Depression)	Strong freshwater influence from mainland river runoff drives northwestward flowing coastal buoyancy current and estuarine-like circulation	Mixture of neritic and subpoplar species; migratory corridor for Pacific salmon; some productive and protected areas for juvenile fish and invertebrate development	Distinguished from area to south by strong freshwater discharge influence
Strait of Georgia	Broad shallow basin surrounded by coastal lowlands (Georgia Depression)	Protected coastal waters with significant freshwater input, high turbidity, and seasonally stratified; very warm in summer	Nursery area for salmon and herring; abundant shellfish habitat; neritic plankton community	Stronger Fraser R. Signature than areas to north or west
Juan de Fuca Strait	Deep trough; a major structural feature accentuated by glacial scour	Semiprotected coastal waters with strong "estuarine-like" outflow current (coast-hugging buoyancy current to north); major water exchange conduit with "inland sea"	Migratory corridor for anadromous fish; moderately productive; mixture of neritic and oceanic plankton species	Much more marine than Strait of Georgia; less "open shelf" than Vancouver Island Shelf
Queen Charlotte Strait	Predominantly shallow (<200 m), high relief area with deeper fjord areas	High current and high relief area; very well mixed; moderate to high salinities with some freshwater inputs in the inlets and fjords	Very important for marine mammals; migratory corridor for anadromous fish; moderate shellfish habitat	More marine than Johnstone Strait; much more shallow with higher relief and higher currents than Queen Charlotte Sound
North Coast Fjords	Deep, narrow fjords cutting into high coastal relief	Very protected waters with restricted circulation and often strongly stratified	Low species diversity and productivity due to poor water exchange and nutrient depletion; unique species assemblages in benthic and plankton communities	Unique physiography and stratification compared to surrounding regions

(Continued on next page)

Table 2
Pacific marine ecosections and their justification criterion (*Continued*)

Marine ecosections	Physiographic features	Oceanographic features	Biological features	Boundary rationale
Hecate Strait	Very shallow strait dominated by coarse bottom sediments; surrounding coastal lowlands	Semiprotected waters with strong tidal currents that promote mixing; dominantly "marine" waters	Neritic plankton communities with some oceanic intrusion; nursery area for salmon and herring; abundant benthic invertebrate stocks; feeding grounds for marine mammals and birds	Marine in nature but much shallower, with associated greater mixing, than areas to the south
Subarctic Pacific	*Includes abyssal plain and* continental rise; a major transform fault occurs along the west margin and a seamount chain trends northwest/southwest	*The eastward flowing subarctic current* bifurcates at coast with northerly flowing Alaska Current; current flow is generally northward throughout the year	*Summer feeding ground for Pacific* salmon stocks; abundance of pomfret, Pacific saury, albacore tuna, and kack mackerel in summer; boreal plankton community	The northern and western boundaries are undefined. The eastern boundary is coincident with the shelf break. The southern boundary is indistinct but is meant to be located
Queen Charlotte Sound	Wide, deep shelf characterized by several large banks and interbank channels	Ocean wave exposures with depths mostly >200 m and dominated by oceanic water intrusions	Mixture of neritic and oceanic plankton communities; northern limit for many temperate fish species; lower benthic production	More oceanic (deep) and marine than Vancouver Island Shelf and Hecate Strait
Transitional Pacific	Includes abyssal plain, and continental rise; also includes spreading ridges, transform faults, triple junction, and plate subduction zone	Area of variable currents; southerly areas may be affected by southward-flowing California Current in summer, but remainder of area characterized by weak and variable currents; Davidson Current along shelf edge flows north in winter, south in summer	Transition zone between southerly, temperate, and northerly boreal plankton communities; mixing of oceanic and coastal plankton communities adjacent to the coastal shelf	The northern boundary is indistinct and approximately coincident with the southern limit of the Alaskan Current (winter). The eastern boundary is at the shelf break. The southern and western boundaries are undefined
Vancouver Island Shelf	Narrow, gently sloping shelf	Open coast with oceanic wave exposures; northward, coast-hugging buoyancy current due to freshwater influence; seasonal upwelling at outer margin	Highly productive with neritic plankton community; northern limit for hake, sardine, northern anchovy, and Pacific mackerel; productive benthic community; rich fishing grounds for benthic fish and invertebrates	More open shelf than Juan de Fuca Strait; more freshwater influence (coastal buoyancy current) than Queen Charlotte Sound

Sources: Modified from Harper et al. (1993); Hirvonen, Harding, and Landucci (1996); and Howes et al. (1996).

to ecosystem classification (Scott et al., 1993). These methodologies, however, differ substantially, due to the unique nature of marine environments.

Terrestrial ecosystem mapping was developed out of a requirement to identify current and historical boundaries of communities, and the abiotic conditions that support them (Cherrill et al., 1995; Conroy & Noon, 1996; Edwards, 1996; Jennings, 1995; Merrill, Wright, & Scott, 1995; Scott et al., 1993). In doing so, it was found that a knowledge of climate, vegetation, soils, and other abiotic properties could be used to predict the occurrence of higher vertebrate species. This knowledge was particularly useful in environments where these species were depleted as a result of human activities (Caicco et al., 1995; Davis & Reiners, 1996; Short & Hestbeck, 1995). The majority of primary producers in terrestrial environments are large—often homogenous—vascular species readily identified by the human eye, and are amenable to small-scale mapping techniques such as airborne and satellite remote sensing (Scott et al., 1993). Consequently, vegetation can be used in the prediction of vertebrate species (bottom up) or physical characteristics such as soils or climate (top down), and forms the basis of terrestrial ecosystem mapping (Scott et al., 1993).

Marine environments, however, are very different. With the exception of the macroalgae in photic environments, primary producers consist of phytoplankton (often bacteria) whose numbers of species are still being estimated and are subjected to constant transport (Norse, 1993). The secondary consumers depending on these phytoplankton are just as diverse and poorly understood, and the cryptic nature of marine food webs continues upward through the large vertebrates (Mann & Lazier, 1996; Thorne-Miller & Catena, 1991). Our knowledge of the life histories of some of the most studied marine vertebrates is still poorer than almost all terrestrial vertebrate species (National Research Council, 1995).

Our lack of biological knowledge is compounded by the pronounced effect of human activities on marine environments. Almost all data collected in marine environments have been affected by anthropogenic activities (Norse, 1993). Considerable amounts of marine data are obtained from fishery catch statistics, where the act of observation (fishing) changes community composition and biomass. The Northeast Pacific is also being studied subsequent to the removal of important herbivores and predators including the Stellar's sea cow *(Hydrodamalis gigas)* and sea otter *(Enhydra lutris)* (Vermeij, 1993). Many populations of nonharvested marine species are thought to have declined, but there is little empirical evidence to support this position (Thorne-Miller & Catena, 1991). Consequently, the use of nonharvested species to describe the "natural state" of ecosystems may be erroneous.

In the Northeast Pacific, humans, plants, and animals arrived simultaneously with the retreat of glaciation. Therefore, there is no natural state in the absence of anthropogenic activities that conservation strategies strive to reproduce. In parts of the coastal Northeast Pacific, indigenous peoples far outnumbered current populations and harvested certain marine species in greater numbers than they are presently harvested (British Columbia, 1992; Cannings & Cannings, 1996).

There is also considerable debate on the importance of biological versus physical determinants in marine systems (Dayton, 1995; Mann & Lazier, 1996; National Research Council, 1995). Until recently, many authors supported the generalization that physical mechanisms and processes are more important than biological processes in defining community and trophic structure, and that pelagic systems are more physically influenced while benthic environments are biologically accommodated (Etter & Grassel, 1992; Ricklefs, 1987; Thorne-Miller & Catena, 1991). There are, however, new studies suggesting that physical processes define most aspects of the marine environment and are more important in benthic systems than originally thought (Harris, 1994; Meyers, 1994; Roughgarden, Pennington, & Alexander, 1994). The importance of the physical determining the biological becomes more noticeable as the scale of observation becomes smaller. The importance of small-scale (large area) perturbations can be seen in what Harris (1994) termed the "horizontal" (or within species) and the "vertical" (or trophic) structure. Physical processes also are more limiting on smaller rather than larger organisms, as smaller species are more affected by viscosity and inertia problems in a liquid medium (Angel, 1994; Mann & Lazier, 1996). Current theory also suggests that, the greater the severity of the physical environment, the greater its effect on biological processes (Dayton et al., 1984; Mann & Lazier, 1996; Roughgarden, Pennington, & Alexander, 1994).

In summary, the following observations suggest that physical and chemical processes control the biotic character of marine systems to a much greater extent than terrestrial environments. Human activities also have altered the biological composition of marine systems to an extent that their natural state often is difficult to characterize. In light of these considerations, the development of the ecounits was based on physical and chemical considerations rather than biological processes.

Creating the Ecounits

The following properties were selected to build the ecounits: wave exposure, depth, subsurface relief, currents, and seabed substrate (Wainwright et al., 1995). These properties were selected on ecological relevance and the availability of a systematic coverage for the study area. Temperature and salinity were not used in the creation of the ecounits, as systematic data for the Pacific coast were not available. Temperature and salinity data for the majority of the study area are expected to be available within the next year. At this time, these properties will be incorporated into the ecounits.

Wave exposure was chosen because it is an indicator of mixing and nutrient transport in the upper water column, and an important constraint on nearshore and shoreline community composition (Kozloff, 1993; Mann & Lazier, 1996). Wave exposure was estimated using a method designed by the Coastal Engineering Research Center (CERC), and exposure categories are presented in Table 3 (CERC, 1977; Howes, Harper, & Owens, 1994).

Depth is a natural consideration for any ecosystem classification, as it is easy to measure and it is a major ecological division. Depth categories were chosen to accurately represent the photic zone, as well as shallow and deeper shelf environments (Table 3). Water depths were obtained from 1:250,000 scale Natural Resource Series maps and Canadian Hydrographic Service (CHS) charts (CHS, 1983, 1987, 1990).

Subsurface relief was included because it is an indirect indication of mixing, and areas with high relief environments provide habitat to many important benthic and demersal organisms, including the lingcod *(Ophiodon elongatus)* and rockfish (*Sebastes* spp.) (Ilg & Walton, 1979). Areas of high relief tend to have irregular bottom morphologies and high elevation ranges; low relief areas have uniform slopes with small elevation gradients. Relief was estimated from CHS charts and bathymetric data sets by comparing benthic surface area to sea surface area. Care was taken to ensure consistency, given the differences in scales and contour intervals between the charts and bathymetric maps.

Currents were identified since they are an important constraint on marine communities and provide an index of water stratification. High current areas increase the avail-

Table 3
Themes and classifications for ecounits
of the British Columbia Marine Ecosystem Classification

Theme	Class[a]	Description
Wave exposure	High (H)	Fetch >500 km. Ocean swell environment
	Moderate (M)	Fetch 50–500 km. Some swell areas; open sounds and straits
	Low (L)	Fetch <50 km. Protected areas; some small sounds and straits
Depth	Photic (B)	0–20 m
	Shallow (C)	20–200 m
	Moderate (D)	200–1,000 m
	Abyssal (E)	>1,000 m
Relief	High (H)	Abundant cover and diversity of habitats
	Low (L)	Smooth or gently undulating bottom
Currents	High (H)	Maximum currents >3 knots (1.54 m/s)
	Low (L)	Maximum currents <3 knots (1.54 m/s)
Substrate	Hard (H)	Bedrock, boulders, cobble, and some sand/gravel areas
	Sand (S)	Sand, gravel/sand, and some muddy areas
	Mud (M)	Mud and sandy mud
	Unknown (U)	Not sampled

Source: After Wainwright et al. (1995).
[a]Letters in parentheses following the class descriptions are coded to the ecounits. For example, MBHLM is a polygon comprised of *M*oderate exposure, photic (*B*) depth, *H*igh relief, *L*ow current, and *M*ud substrates.

ability of nutrients to sessile organisms, almost always are well mixed, and typically represent areas of high biological productivity (Dyer, 1973; Pritchard, 1995). Information on current velocity was hindered by the lack of detailed and systematic information outside of the Strait of Georgia and Juan de Fuca Strait (Figure 1). As a result, high current areas were defined as areas where current velocities frequently exceed 3 kn. This information was obtained from CHS publications, which include charts and sailing directions (CHS, 1987, 1990).

Seabed substrate is an important constraint on benthic and demersal communities, and yields an indirect index of substrate mobility. For example, bottom areas consisting of mud are usually an indicator of low-energy, depositional conditions, whereas rock or gravel substrates can indicate higher current activity and nondepositional environments. Community response to substrate is most evident within the photic zone, but certain species such as the English (lemon) sole *(Pleuronectes vetulus)* and starry flounder *(Platichtys stellatus)* occur in conjunction with sand and silt substrates in deeper areas (Lamb & Edgell, 1986; Tyler et al., 1987).

The preferred source of seabed substrate was the Geological Survey of Canada surficial sediment distribution maps (Barrie, Luternauer, & Conway, 1989a,b,c,d; Conway, Barrie, & Bornhold, 1985a,b; Luternauer, 1986; Luternauer & Murray, 1983; Luternauer, Barrie, & Conway, 1989; Pharo & Barnes, 1976). These maps provide good coverage of Hecate Strait, Queen Charlotte Sound, Vancouver Island Shelf, and the Strait of Georgia. There are no systematic sediment data for the Continental Slope, Subarctic Pacific, and Transitional Pacific ecosections. These areas cannot be assumed to be muddy and were cataloged as unknown (McCoy & Barnes, 1987; Price, 1977; Scrimger & Bird, 1969) (Table 3). For the remaining areas in shallow water (<200 m) and where there are no surficial sediment maps, CHS chart substrate data were used. Although these data are obtained by lead line sampling and are less reliable than the surficial geology maps, they were considered adequate for this project (Wainwright et al., 1995).

Information on each of the physical properties was transferred from the various sources onto 1:250,000 scale base maps and digitized into a Geographic Information System (GIS). The ecounits were created by employing a GIS model to combine the five physical data sets into a single digital map using the overlay, or "cookie cutter" approach. Each ecounit is a combination of the five physical properties. For example, the ecounit HDLLS is composed of *H*igh exposure, *D*eep bathymetry, *L*ow relief, *L*ow current, and *S*and substrate (Tables 3 and 4).

A total of 619 ecounits were identified and mapped for the Canadian portions of the Pacific coast (Figure 2). They can be grouped into 65 repetitive classes on the basis of their combinations of the five physical properties (Table 4). The ecounit HELLU accounts for 74% of the total ecounit area, and represents abyssal environments where there is almost no information on substrate, relief, and current (Figure 2; Table 4).

Analysis of the Ecosections Using the Ecounits

Two types of analysis were used to evaluate the ecosections and their boundaries. The first method reviewed the areal distribution of the five physical (ecounit) properties within each ecosection. The second involved an analysis of the internal homogeneity of the ecosections, based on the number and type of ecounits within each ecosection.

Results

The ecosections were initially evaluated by reviewing the areal distribution of the five physical properties within each ecosection. The distribution of the properties for each ecosection is plotted in Figure 3. The following discussion examines the results of this analysis.

Current

High current environments do not account for a large portion of the areas within any of the ecosections (Figure 3). Ecosections that have the largest areas of high current include Johnstone Strait, Queen Charlotte Strait, and Juan de Fuca Strait. A greater percentage of high currents occur in these environments as they are constricted (narrow) waterways that drain the inland waters of the Georgia Basin. The remaining ecosections exhibit a very low proportion of high current areas. These results can be somewhat misleading because the regional current data set was based on a threshold of 3 kn, which does not highlight many areas with currents slightly less than 3 kn (Wainwright et al., 1995).

Table 4
Summary of the ecounit classes in km², and the percentage of total area

Ecounit[a]	Area (km²)	Percent (%)	Ecounit[a]	Area (km²)	Percent (%)
HBHHH	79.05	0.02	LBLHS	30.53	0.01
HBHLH	1254.37	0.28	LBLLM	138.27	0.03
HBHLS	1055.85	0.23	LBLLS	403.39	0.09
HBLHH	23.67	0.01	LCHHH	98.54	0.02
HBLHS	80.65	0.02	LCHHS	99.67	0.02
HBLLH	552.76	0.12	LCHLH	681.68	0.15
HBLLS	870.09	0.19	LCHLM	701.25	0.15
HCHHH	198.52	0.04	LCHLS	184.65	0.04
HCHHS	71.05	0.02	LCLHH	95.29	0.02
HCHLH	8016.82	1.77	LCLHM	45.69	0.01
HCHLM	122.02	0.03	LCLHS	110.84	0.02
HCHLS	4576.8	1.01	LCLLH	452.91	0.10
HCLHH	218.52	0.05	LCLLM	4800.17	1.06
HCLHS	258.89	0.06	LCLLS	826.43	0.18
HCLLH	12091.77	2.67	LDLLM	5074.22	1.12
HCLLM	3625.65	0.80	LDLLS	356.46	0.08
HCLLS	27246.82	6.01	MBHHH	30.61	0.01
HCLLU	894.11	0.20	MBHLH	417.26	0.09
HDHHS	15.61	0.00	MBLLH	452.08	0.10
HDHLH	569.31	0.13	MBLLS	1136.44	0.25
HDHLS	151.36	0.03	MCHHH	118.64	0.03
HDHLU	193.83	0.04	MCHLH	1434.88	0.32
HDLHH	163.05	0.04	MCHLM	663.16	0.15
HDLLH	7838.29	1.73	MCHLS	599.24	0.13
HDLLM	1962.52	0.43	MCLHH	41.81	0.01
HDLLS	8776.53	1.94	MCLHS	83.72	0.02
HDLLU	8847.39	1.95	MCLLH	676.07	0.15
HEHLU	493.3	0.11	MCLLM	2730.35	0.60
HELLH	327.54	0.07	MCLLS	1146.79	0.25
HELLU	335516.8	74.00	MDHLM	92.72	0.02
LBHLH	242.3	0.05	MDLLM	2761.94	0.61
LBHLM	135.54	0.03	MDLLS	404.23	0.09
LBLHH	51.1	0.01	Total	453411.8	100.0

[a]Ecounit codes can be deciphered using Table 3.

Depth

The variation and distribution of depth between and within ecosections is outlined in Figure 3. The Continental Slope ecosection is a mix of abyssal, deep, and shallow depths and represents a transitional zone between the abyssal Subarctic Pacific and Transitional Pacific ecosections, and the shallower ecosections of the Pacific Marine Shelf ecoregion (Figure 1). The Hecate Strait and Vancouver Island Shelf ecosections are the shallowest,

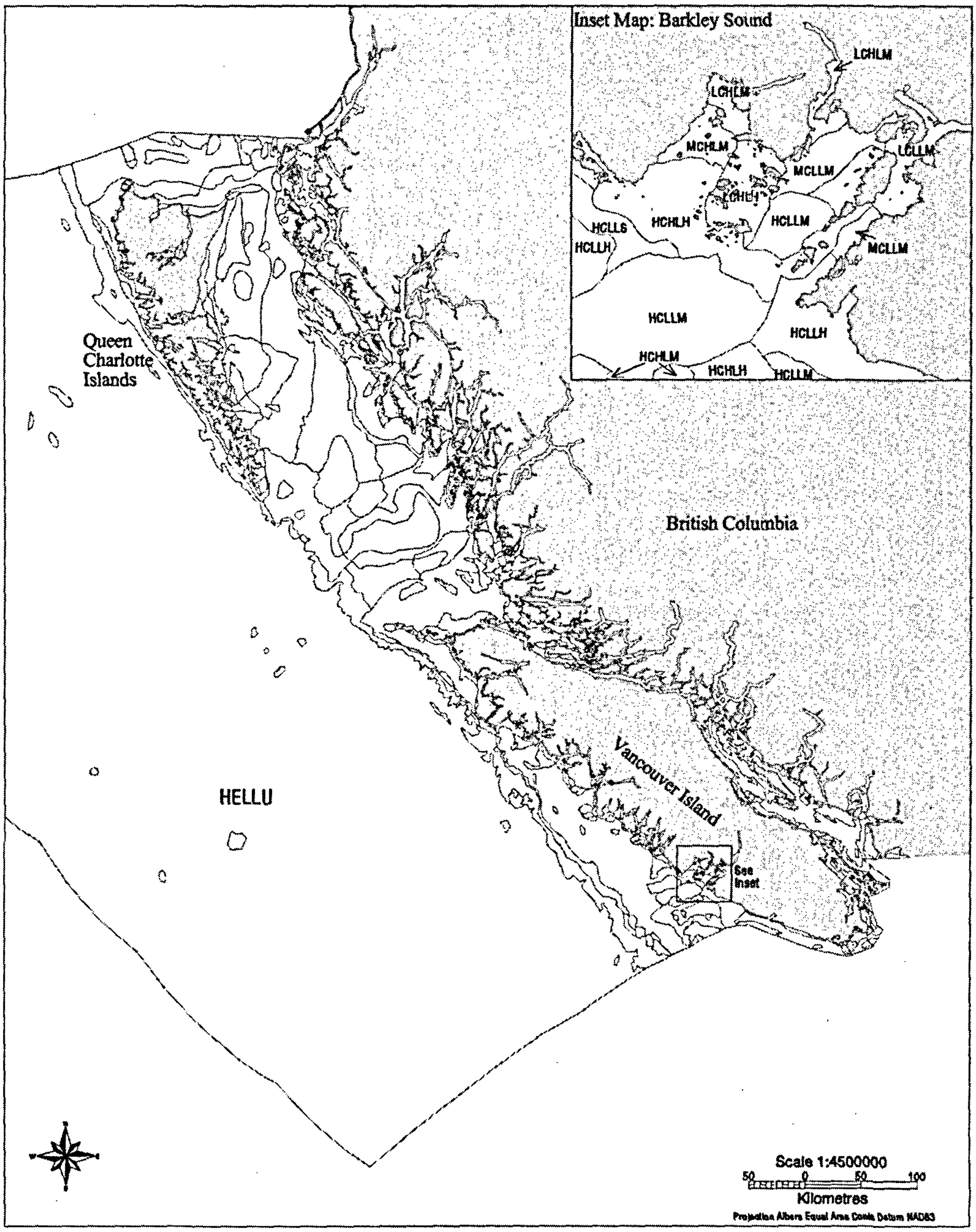

Figure 2. The Pacific marine ecounit boundaries. The scale of the ecounits is 1:250,000, and a legend is not shown, as there are 65 possible combinations of current, depth, wave exposure, relief, and substrate for the 619 ecounits. An explanation of the 65 classes is supplied in Table 4, and the ecounit, HELLU, is shown for illustration purposes.

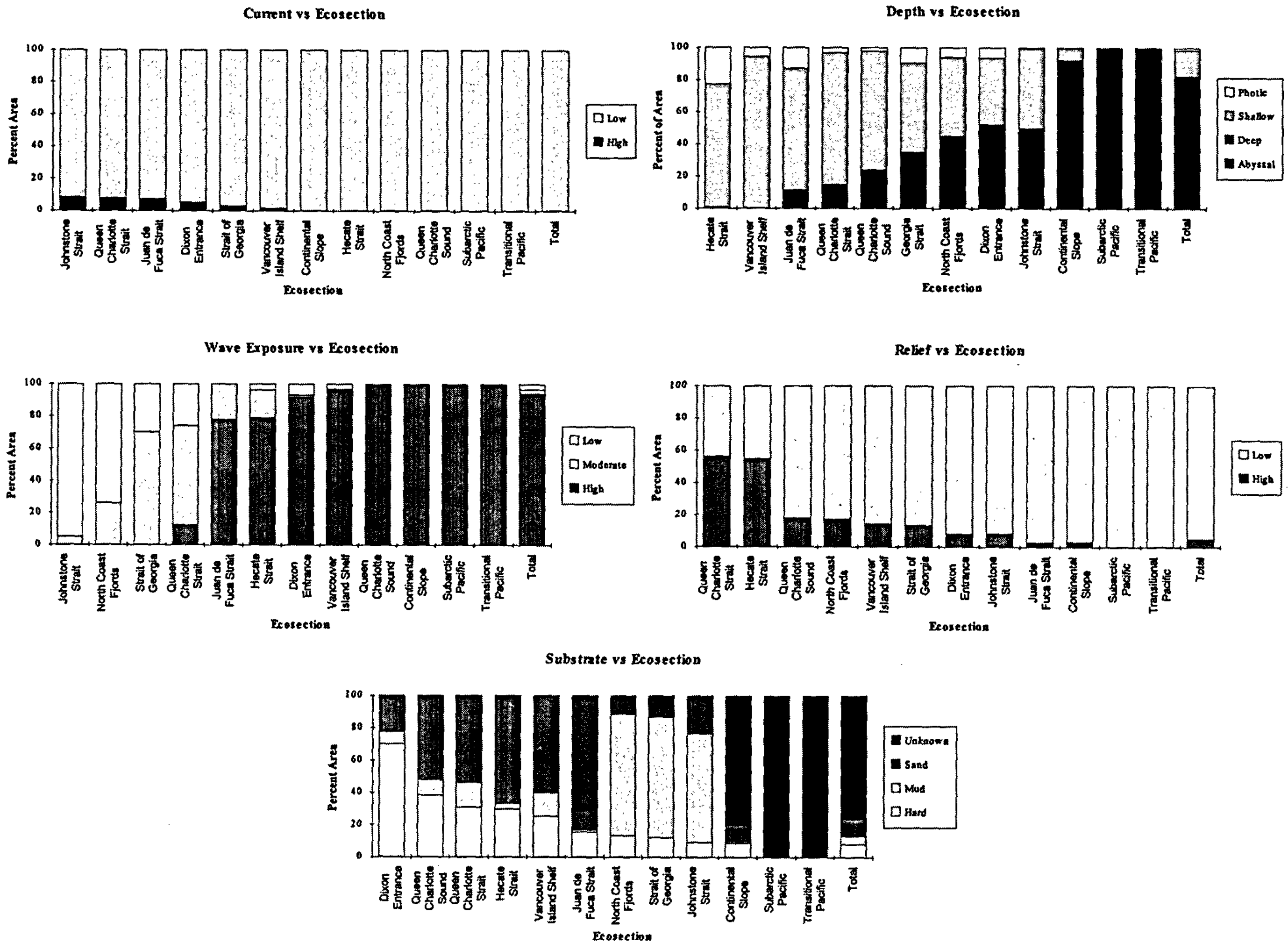

Figure 3. Distribution of the physical ecounit themes by ecosection.

with over 20% of the Hecate Strait ecosection composed photic depth (0–20 m). The Johnstone Strait, Dixon Entrance, and North Coast Fjords ecosections generally comprise an equal mix of shallow and deep depths. The remaining ecosections are dominated by shallow depths, with fewer amounts of deeper and photic depths. The North Coast Fjords ecosection is much deeper than the adjacent Hecate Strait and Queen Charlotte Sound ecosections.

Exposure

The Johnstone Strait and North Coast Fjords ecosections are the most protected (Figure 3). The Johnstone Strait ecosection has the lowest exposure, due to its narrow channels and fjords that reduce fetches to less than 10 km in most areas. The North Coast Fjords ecosection has some moderate exposure areas as a result of the length of many fjords that comprise this area. The Strait of Georgia and Queen Charlotte Strait ecosections are composed of predominately moderate exposures, with lesser amounts of low exposure, and a small amount of high-exposure areas in the latter. Exposed ecosections include Subarctic Pacific, Transitional Pacific, Continental Slope, Dixon Entrance, Queen Charlotte Sound, and Vancouver Island Shelf. The remaining Hecate Strait and Juan de Fuca Strait ecosections are dominated by high exposures, with a minor amount of moderate exposures.

Relief

The distribution of subsurface relief within the ecosections is outlined in Figure 3. The Hecate Strait and Queen Charlotte Strait ecosections exhibit the greatest variation in relief, with over 50% of their areas composed of high relief. Ecosections with between 10% and 20% of high relief areas include Queen Charlotte Sound, North Coast Fjords, Vancouver Island Shelf, and the Strait of Georgia. The remaining ecosections have less than 10% high-relief areas.

Substrate

The variation and distribution of bottom substrate types between ecosections is outlined in Figure 3, and suggest that the ecosections can be categorized into five broad groups. Ecosections dominated by mud include North Coast Fjords, Strait of Georgia, and Johnstone Strait. These environments have significantly less amounts of sand and hard substrate. The Juan de Fuca Strait ecosection is somewhat unique as it is the only ecosection consisting of more than 80% sand. Ecosections consisting of mixes of sand and hard substrates, with a minor amount of mud, include Queen Charlotte Strait, Queen Charlotte Sound, and Vancouver Island Shelf. The substrates of the Continental Shelf, Subarctic Pacific, and Transitional Pacific ecosections are unknown, due to a lack of information. The Dixon Entrance ecosection is dominated by hard substrate, with a minor amount of sand.

The dominant characteristics of each ecosection are summarized in Table 5. Apart from the Subarctic Pacific and Transitional Pacific ecosections, there are significant differences between these areas. In most cases, the ecosections differ from each other by at least two or three different physical properties. For example, the Johnstone Strait, North Coast Fjords, and Strait of Georgia ecosections have distinct current and exposure regimes, but similar depths, subsurface relief, and substrates. Transitional ecosections

Table 5
Summary of the dominant classes of each criteria within each ecosection

Ecosection	Depth	Current (% high)	Exposure	Relief	Substrate
Johnstone Strait	Shallow/deep	9	Low	Low	Mud
Continental Slope	Abyssal/deep	<1	High	Low	Unknown
Dixon Entrance	Deep/shallow	5	High	Low	Hard
Hecate Strait	Shallow/photic	<1	High	High	Sand/hard
Queen Charlotte Strait	Shallow	8	Moderate/low	High	Sand/hard
Juan de Fuca Strait	Shallow	7	High/moderate	Low	Sand
North Coast Fjords	Shallow/deep	<1	Low	Moderate	Mud
Queen Charlotte Sound	Shallow	<1	High	Moderate	Sand/hard
Strait of Georgia	Shallow/deep	3	Moderate/low	Moderate	Mud
Subarctic Pacific	Abyssal	0	High	Low	Unknown
Transitional Pacific	Abyssal	0	High	Low	Unknown
Vancouver Island Shelf	Shallow	2	High	Moderate	Sand/hard

linking the Strait of Georgia with the Juan de Fuca Strait, Johnstone Strait, and Queen Charlotte Strait ecosections have similar current regimes, but different exposure, relief, and substrate characteristics.

Ecosection Homogeneity

The homogeneity of the ecosections was assessed by comparing the total number of ecounits within an ecosection to the total number of repetitive ecounit classes within an ecosection. The results of these comparisons are outlined in Figure 4. Where there is a large difference between the number of ecounits and the number of ecounit classes, the ecosection is considered to exhibit a high degree of internal homogeneity. Those ecosections that exhibit minimal differences are thought to reflect greater internal variations.

Six of the ecosections display a high degree of internal homogeneity: North Coast Fjords, Queen Charlotte Sound, Strait of Georgia, Vancouver Island Shelf, and Continental Slope. The Juan de Fuca Strait, Queen Charlotte Strait, and Johnstone Strait ecosections demonstrate a high degree of variability and are considered to represent transitional environments. These three ecosections are located between the inland waters of the Georgia Basin and the more open waters of the Pacific Ocean, and tend to display characteristics of both their neighboring ecosections. The Dixon Entrance ecosection is more homogenous than these transitional ecosections, but displays a greater variability than the other ecosections. The variability within the Dixon Entrance ecosection is a function of large freshwater inputs driving a large estuarine-like current system.

The results of this analysis are encouraging, and suggest that the ecosections of the BCMEC are distinct and valid marine ecological regions. The ecounits and the

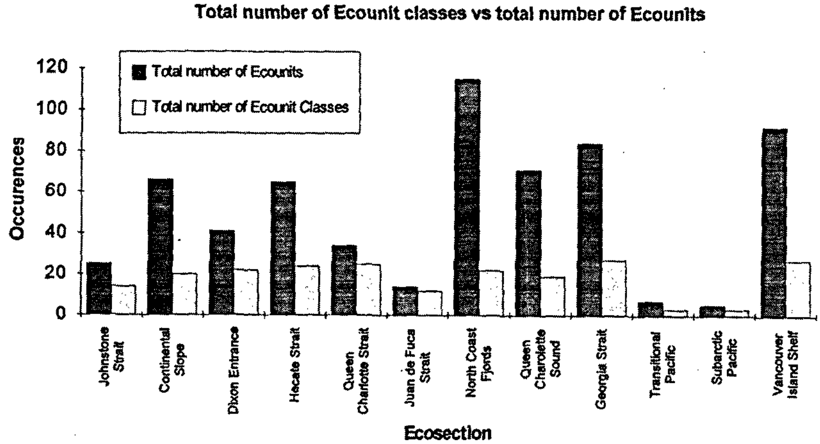

Figure 4. Comparison of ecounit classes to ecounits for each ecosection. The greater the difference between *total number of ecounits (up to 619)* and *total number of ecounit classes (up to 65)* indicates greater homogeneity within the ecosection.

properties used to define them have resulted in a better delineation of the ecosections and definition of their boundaries.

Discussion

The ecounits are a powerful new tool for marine and coastal management, planning, and the identification of marine protected areas. The ecosections and ecounits of the BCMEC have been used to assess the representation of marine protected areas in British Columbia (Zacharias & Howes, 1998). It is expected that they also will be used to locate new representative and distinctive candidate sites for the Canada–British Columbia Marine Protected Areas Strategy. This methodology, in combination with the traditional site- and species-specific approach to the identification of marine protected area candidate sites, will permit the systematic examination of over 453,000 km^2 of marine area.

There is, however, room for improvement and further refinement of the ecounits. As discussed above, temperature and salinity will be incorporated into the classification within the next year. There also are other developments under way, which include the further subdivision of the ecounits into vertical and horizontal components. The present form of the ecounits assumes homogeneity in the vertical components of the water column, where, in reality, the changes in the vertical relationship between species and habitats often do not correlate with changes in the horizontal relationship (Mann & Lazier, 1996; Pickard & Emery, 1988). To remedy this problem, the additional subdivision of the ecounits into their vertical components is under consideration. How this will be accomplished is currently under review, but several solutions have been suggested. Taylor & Roff (1997) have suggested the separation of the benthic (or physiographic) from the pelagic (or oceanographic) environments, since these two realms are fundamentally different as a result of their two- and three-dimensional natures (Mann & Lazier, 1996; Taylor & Roff, 1997). These environments are not biologically separate, however, as many benthic sessile organisms release motile and nonmotile larvae and reproductive cells into the marine environment, and many pelagic organisms (e.g., baleen whales) depend on the benthos for food and habitat. Pelagic (oceanographic) parameters identified by Taylor and Roff (1997) include salinity, temperature, steep gradients or anomalies in temperature or salinity, irradiance (light), water column mixing and stratification, nutrients, tidal activity and currents, and wave exposure. Benthic (physiographic) features include latitude, relief, and substrate (Taylor & Roff, 1997).

The long-term objective of the BCMEC is to establish the ecological links between the physical characteristics of the marine environment and the habitat requirements of the species that inhabit these environments. While there still is much work to be accomplished, there is evidence that the ecosystem based approach presented in this article is a step toward this objective. The incorporation of additional physical, chemical, and biological data is under way, and will ideally improve the ecounit level of the BCMEC to a point where broad based inferences on community composition and habitat type can be made.

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