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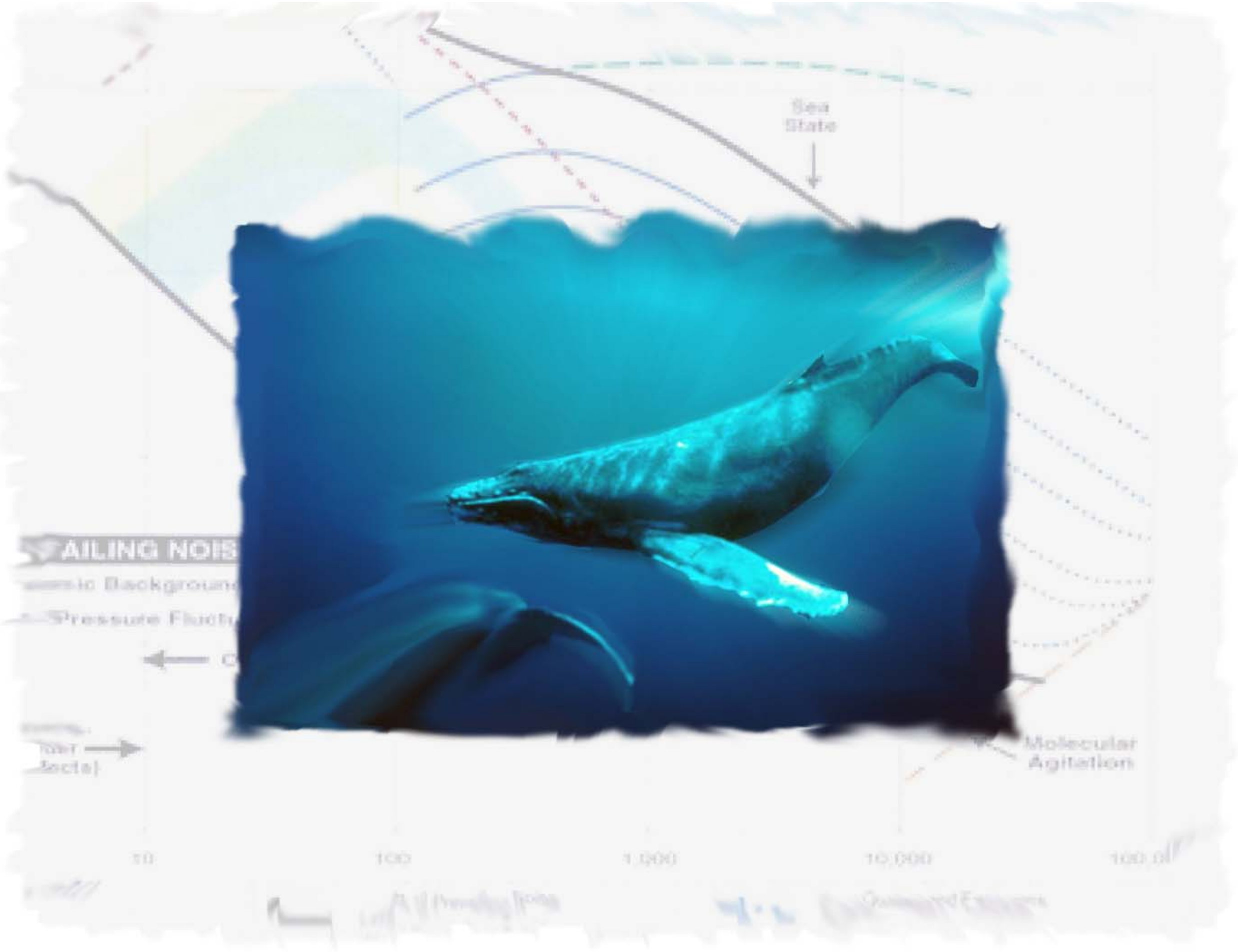

Noise Levels and Sources in the Stellwagen Bank National Marine Sanctuary and the St. Lawrence River Estuary

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Ocean Service
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Marine Sanctuaries Division

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About the Marine Sanctuaries Conservation Series

The National Oceanic and Atmospheric Administration's Marine Sanctuary Division (MSD) administers the National Marine Sanctuary Program. Its mission is to identify, designate, protect and manage the ecological, recreational, research, educational, historical, and aesthetic resources and qualities of nationally significant coastal and marine areas. The existing marine sanctuaries differ widely in their natural and historical resources and include nearshore and open ocean areas ranging in size from less than one to over 5,000 square miles. Protected habitats include rocky coasts, kelp forests, coral reefs, sea grass beds, estuarine habitats, hard and soft bottom habitats, segments of whale migration routes, and shipwrecks.

Because of considerable differences in settings, resources, and threats, each marine sanctuary has a tailored management plan. Conservation, education, research, monitoring and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the National Marine Sanctuary Program. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and cultural sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate.

Noise Levels and Sources in the Stellwagen Bank National Marine Sanctuary and the St. Lawrence River Estuary

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CONTENTS

TOPIC **PAGE**

ABSTRACT

Although ambient (background) noise in the ocean is a topic that has been widely studied since pre-World War II, the effects of noise on marine organisms has only been a focus of concern for the last 25 years. The main point of concern has been the potential of noise to affect the health and behavior of marine mammals. The Stellwagen Bank National Marine Sanctuary (SBNMS) is a site where the degradation of habitat due to increasing noise levels is a concern because it is a feeding ground and summer haven for numerous species of marine mammals. Ambient noise in the ocean is defined as "the part of the total noise background observed with an omnidirectional hydrophone." It is an inherent characteristic of the medium having no specific point source. Ambient noise is comprised of a number of components that contribute to the "noise level" in varying degrees depending on where the noise is being measured. This report describes the current understanding of ambient noise and existing levels in the Stellwagen Bank National Marine Sanctuary.

Introduction

Ambient noise in the ocean is a topic that has been widely studied since the 1940s. Over the last 25 years the effects of noise on marine organisms has become a concern. The primary issue has been the potential of noise to adversely affect marine mammals. The Stellwagen Bank National Marine Sanctuary (SBNMS) and upper estuary of the St. Lawrence River are sites where the degradation of habitat due to increasing noise levels is a concern because they are feeding grounds and summer havens for numerous species of marine mammals. In an effort to provide information for better sanctuary management this report describes the current understanding of ambient noise and existing levels of ambient noise and its relationship to marine mammals in the Stellwagen Bank National Marine Sanctuary and the designated marine park area of the Upper St. Lawrence River Estuary.

Noise Pollution and Marine Mammals

Noise is defined as “unwanted sound” (Au, 1993). As such, the ability to quantify noise levels (NL) is important to any sonar system, be it anthropogenic or biotic. The purpose of any sonar system is to detect signals in noise. The measure of this ability is critical to all sonars and is measured as the ratio of the signal of interest to the noise level. This is commonly known as the signal-to-noise ratio or SNR. For this and other reasons, ambient [background] noise in the ocean is a topic that has been widely studied since pre-World War II. The effects of noise on marine organisms, however, has only been a focus of concern for the last 25 years, the main concern being its potential effects on marine mammals. It was this issue that led the National Research Council to create the Committee on Low-Frequency Sound and Marine Mammals in 1992 (NRC, 1994). The committee’s charge was to “review the current state of knowledge and ongoing research on the effects of low-frequency [0.1 to 1kHz] sound on marine mammals and to advise the sponsors of the report about the effects of low-frequency sound on marine mammals” (NRC, 1994).

The committee was able to find virtually no quantitative information regarding noise that could be of use in assessing the effects of noise on marine mammals. Since that time, interest in the effects of noise on commercial species of fish and benthic organisms has grown, yet information remains sparse. Perry (1998), however, compiled an excellent review of the various reports regarding potential impacts of anthropogenic noise on cetaceans.

Among cetaceans, coastal species are most immediately affected by human disturbance that degrades or destroys their habitat. Noise pollution is a factor that is only recently becoming recognized as a significant potential danger. Cetaceans, especially small gregarious Odontocetes, make extensive use of sound in their daily lives. Sounds are used for social communication, to ensure pod cohesion, navigation, and detecting, identifying and capturing prey. It has long been recognized that Odontocetes and Mysticetes are highly sensitive to sound and compared to humans, can receive and emit acoustic signals over a very wide frequency spectrum.

Worldwide it is estimated that there are 295 communities in 65 countries that support the majority of whale watching activities, leading to considerable seasonal increases in the density of small to large size boat traffic (Hoyt, 1994, 2001). In addition, many such areas are in the vicinity of sites also used for other vacationing purposes, which contribute additional traffic. The propulsion systems of these various crafts are a major source of low-frequency underwater noise that travels over considerable distances. The major whale watching areas are precisely those favored by the whales for feeding, socializing, resting, or even calving and rearing of young. Therefore, there may be the potential for excessive background noise to interfere with the biology of several species, especially where populations are restricted within such areas. The impacts of noise may have consequences for the whales' ecology (affecting animal energetics), physiology and health (audiologically or neurologically related), acoustics (affecting the structure and use of sounds as they relate to the acoustic environment), anatomy (affecting hearing organs) or some combination of these (Scheifele et al., 2004).

Acoustic behavioral changes relative to sound levels and reverberation have shown that cetaceans change their signal structure to accommodate differences in acoustical environments (Au, 1993; Scheifele, 1988a; Scheifele et al, 2004) and in the presence of boat traffic (Lesage, 1993) but the limits, if any, to which they can adapt to increasing noise levels is unknown. Studies of audiology have shown that mammalian hearing can certainly be impaired by increases in sound levels (Fay, 1988; Ketten and Wartzok, 1990). Because the basic structure of the whale ear is similar to that of land mammals, it is likely that they sustain substantial hearing loss with age, trauma, disease, and exposure to organo-toxins. However, it is also possible that *aquatic* ear adaptations, which protect against baro- or impact trauma, ameliorate noise or degenerative loss. There is an extensive body of research on how hearing in mammals is lost from exposure to noise, disease, and chemical agents. Changes that occur in the ear anatomy that are diagnostic for each type of impact are well documented.

While some data suggest Odontocete ears may be somewhat resistant to hearing damage, it is clear from other studies that they are not impervious. Ears from humpbacks that survived underwater explosions, but died later from non-auditory causes, clearly had extensive auditory trauma that were consistent with permanent and profound hearing loss, including temporal bone fractures, ruptured round windows, and ear drum lesions (Ketten et al., 1995). These data show that adaptations that prevent barotrauma do not provide immunity from severe pressure trauma; therefore, it remains open what pressures at what frequencies will induce precipitous, irreversible damage to whale ears. In addition, there is evidence that suggest dolphins can lose hearing from long-term exposures to relatively low-level stimuli. In a second pilot study, inner ears from a long-term captive dolphin with a documented high frequency hearing loss were examined after the dolphin's death for pathologies related to the loss (Ketten et al., 1995). CT, MRI, and histological studies of these ears showed cell loss and laminar consistent with presbycusis, the progressive sensorineural hearing loss that accompanies old age in humans (Ketten et al., 1995). The primary mechanism behind presbycusis is cellular fatigue from cumulative noise exposures; that is, repeated exposures to sound induce temporary threshold shifts (TTS) that with time produce a permanent hearing loss. The captive dolphin had normal hearing in earlier behavioral audiograms and had no known history of high noise exposure. The location, nature, and degree of neural degeneration in its ears showed a substantial, progressive, hearing loss that began in the high frequency regions of the ear. This too is consistent with the pattern commonly observed in humans (Ketten et al., 1995).

Blind frequency-position estimates of the elder animal's hearing loss (without prior knowledge of the precise audiogram) predicted a profound loss for all frequencies >58 kHz. Available records show that over a 12-year period, the dolphin's responses shifted from normal responses for all frequencies up to 165 kHz to no functional hearing over 60 kHz at age 28. For this animal at least, there is a clear indication that significant hearing loss occurred that is attributable to cumulative, noise induced changes that occur in the ear with age. Finally, in a related study of 39 ears from both captive and wild marine mammals, evidence was found for both active infections and permanent inner ear damage, which was consistent with previous labyrinthine disease. In other words, despite any inherent evolved resistance to TTS, noise at some level and some form of pathologic agents can produce temporary to profound hearing loss in dolphins and whales.

Stellwagen Bank National Marine Sanctuary

The point of concern before the National Marine Fisheries Service and the Sanctuaries Division of NOAA is precisely the potential adverse effects that high noise levels may present to the cetacean species inhabiting the Stellwagen Bank National Marine Sanctuary (SBNMS). The SBNMS is a major cargo-shipping route and holds a number of marinas and major harbors. The central part of that range is seasonally dedicated to whale watching and recreational activities. In the summer season, numerous daily trips are made to the whale watching grounds (including the National Undersea Research Center and the North Atlantic and Great Lakes (NURC NA&GL) Aquanaut Program monitoring sites). In addition, ferries, small pleasure craft and fishing vessels use these same waters every day. Noise pollution has recently been recognized as a potential limiting factor in sustaining the yearly whale population in the SBNMS.

The SBNMS being a feeding ground and summer haven for numerous species of marine mammals and commercial fish species is a natural site where concern over the degradation of habitat due to increasing noise levels is appropriate. Moreover, the SBNMS management staff, National Marine Sanctuaries Division, National Marine Fisheries Service (NMFS) and National Oceanic and Atmospheric Administration (NOAA) national offices have all expressed concern that rising noise levels in the SBNMS could be detrimental to the organisms that inhabit the bank. They are also concerned that increasing noise levels in both the oceans and coastal areas constitute a current trend of serious magnitude.

Historical Context

The body of acoustical research regarding ambient noise in the oceans is extensive, having begun in the late 1940s (Knudsen et al., 1948) and continuing today (Clay and Tolstoy, 1987;George, 2000). Ambient noise in the ocean is defined as "the part of the total noise background observed with an omnidirectional hydrophone, which is not due to the hydrophone and its manner of mounting called "self-noise" or to some identifiable localized source" (Urick, 1983). It includes anthropogenic, biological, meteorological, hydrographic and seismic sources. Quantitative assessments of ambient noise have been relatively easy to accomplish (Anderson, 1958; Wenz, 1962; Greene and Buck, 1964; Fox, 1964; Urick et al., 1972; Nichols, 1979). In the past, the study of noise in the sea was of interest, primarily for military purposes. In the early 1970s the concern shifted to the effects of noise on marine organisms and specifically marine mammals (Payne and Webb, 1971; Reeves, 1977; Myrberg, 1978; Acoustical Society of America, 1981). Since that time the global economy has significantly changed causing the merchant fleet to expand accordingly. The world's military fleets have also expanded. The advent of eco-tourism has caused whale watching, nature tour vessels, cruise ships, and commercial fishing fleets to increase as well in recent years. Moreover, the size and hull-types of vessels have changed since 1970. Supertankers, cannery vessels, larger Fleet Ballistic Missile (FBM) submarines and fast Frigates have all been added to the world fleet. Recently twin-hulled fast (jet wash) catamarans have begun to come on-line as ferries and whale watching vessels.

All of these additional vessels along with the accompanying changes to hull-power plant and propeller configurations have undoubtedly increased the noise level in the oceans. Offshore drilling, construction and scientific research have all added to the milieu, as have changes to advanced military sonar systems. The use of acoustic harassment devices is creating additional noise. It has been estimated that oceanic noise has risen by some 10 decibels in a span of 25 years (NRDC, 1999); however, this figure is purely conjecture.

In accordance with the Marine Mammal Protection Act of 1972 and the Endangered Species Act of 1973 the National Marine Fisheries Service (NMFS) is considering the use of a "180 dB re 1 uPa criterion" as a sound level, above which adverse effects on marine mammals would likely occur. The criterion would be used to limit acoustical operations and research in U.S. waters. This criterion is being revisited from at least two major perspectives. First, this would encompass all underwater activities. Second, the actual effects on the hearing and behavior of marine mammals are unknown at this level. The latter is based upon a number of studies conducted on various species of Cetacea (Malme et al., 1984; Richardson et al., 1986; Miles et al., 1987; Scheifele et al., 1999; Ljungblad et al., 1988; Richardson and Malme, 1993). In 1994 discussions regarding the effects of noise on the behavior of marine mammals became official with amendments to the Marine Mammal Protection Act that affected scientific research permits (NRDC, 1999).

In 1994 the National Research Council suggested that a list of habitat areas currently exposed to high levels of anthropogenic noise be compiled. The National Resources Defense Council (NRDC) has compiled a preliminary list. One of the "acoustical hotspot" sites identified by this report is the Great South Channel. No further effort has been expended on updating or maintaining such a list by any federal agency to date. Very little research is currently being done on identifying significantly noisy sites, determining actual noise levels in the oceans (and particularly coastal zones), determining the actual physical effects of noise on various marine organisms or determining behavioral effects as the result of noise. Research within a few of the already designated sites is also scarce although it continues in the St. Lawrence River estuary and within the SBNMS (Scheifele et al., 1999). Moreover, issues regarding the measurement of noise, hearing in marine organisms, appropriate scales to use in the measurement of noise and hearing, acoustical behavior of marine organisms and the impacts of anthropogenic noise remain unresolved with few quantitative results to resolve them.

Ambient Noise

Ambient noise is an inherent characteristic of the medium having no specific point source. It is comprised of a number of components that contribute to the "noise level" (NL) in varying degrees depending on where the noise is being measured. The noise level is a measure of intensity however, it is practically calculated as the rms pressure of a plane wave relative to a reference pressure of 1 *u*Pa in 1 Hz frequency bands across some spectrum (Urick, 1983). In the case of underwater sound the reference intensity commonly used is 1 *u*Pa. Acoustic intensity is the primary measure of sound at any given frequency.

$$NL = 10 \log I/I_{ref}$$

The term acoustic intensity infers a measure of power per unit area. Intensity is proportional to the mean squared pressure or rms pressure. Since hydrophones actually sense pressure and translate pressure fluctuations into voltages (which can be displayed by electronic devices such as spectrum analysers), pressure measurements are of great importance. The accepted reference pressure is used as the standard to proportionalize the actual pressure registered by the hydrophone. This quantity is the NL. Specifically, the NL of interest in underwater acoustics is the background or ambient noise level.

The precise measurement of ambient noise can be a difficult task since all self-noise of the measuring hydrophone must be quantitatively accounted for. Nevertheless, with some care ambient noise levels may be determined without the use of overly elaborate equipment (Au, 1993). Ambient noise characteristics differ at different frequencies and under varying conditions. It is highly variable in shallow water where the primary sources of noise (such as meteorological, hydrographic, or anthropogenic sources) change and the dominant source (at that time) drives the frequency spectrum and associated noise level. Measurements taken in bays and harbors indicate that anthropogenic noise, biologics, and tidal noise add to the sources that normally contribute to deep water ambient noise levels to create a more noisy acoustic environment (Anderson and Gruber, 1971; Scheifele et al., 1997; Scheifele and Michaud, 1999). Generally the noise field in coastal waters tends to be dominated across the spectrum by wind speed and wave height (Piggott, 1965). The exception to this is during times when vessel traffic or biologics, such as whales, are present.

Components of Ambient Noise

Ambient noise varies greatly across a broad frequency spectrum from 1 Hz to 100 kHz. This variation is the result of erratic conditions due to various sources that may dominate specific parts of that spectrum (Wagstaff, 1973). These sources include: tides, hydrostatic effects of waves, seismic disturbances, turbulence, anthropogenic disturbances, thermal noise, meteorological disturbances, biologics, and absorption and reflection characteristics. The latter sources are specifically applicable to shallow waters. Analysis of fluctuations in ambient noise shows that the overall frequency spectrum usually consists of two frequency domains of different physical character (Furduev, 2000). The low-frequency realm is controlled by variations in wind speed while the high-frequency sector is governed by surface scatter (Furduev, 2000).
The low-frequency end of the spectrum can be dominated by changes in hydrostatic pressure that result from tides and currents. Tides and currents can cause flow-induced noise that can be difficult to predict. In addition, tides produce changes in water temperature that are read by piezoelectric hydrophones as changes in pressure (Urick, 1983). Hydrostatic pressure changes caused by waves and currents are sources of noise at the surface and at depth. The hydrostatic pressure changes that occur on the bottom are also a function of bottom type and topography.

Another source of very low frequency (infrasonic) noise below 1 Hz is seismic disruption. This noise source is particularly relevant to deep ocean environments. It can be the result of the "normal" seismic unrest of the earth or of transient seismic events such as earthquakes and volcanic activity. Since the frequencies emitted by these events are very low the noise may be transmitted over very long distances.

Turbulence describes an irregular flow of water in the form of random currents. These currents may be deep or shallow and occur in many forms such as eddies and longitudinal flows. They consist of rapid and significant pressure changes whose effects may be felt at great distances from the turbulent flows themselves. Although the radiated component of turbulent flows is of little significance acoustically the noise within the currents is of significance. The resulting pressure changes are highly varied (Wenz, 1962). As with seismic disturbances, turbulence has a greater effect on deep ocean noise than in shallow waters.

Still another source of ambient noise is thermal noise, which can limit the sensitivity of a hydrophone in measuring noise levels. Thermal noise is the result of the molecular interactions occurring in seawater (Mellen, 1952). Thermal noise is most likely to impact infrasonic (less than 20 Hz) frequencies.

Between 500 Hz and 25 kHz the ambient noise spectra is dominated by the effect of wind and surface waves. This was observed by Knudsen et al. (1948) as early as 1947. Wind has a direct effect on sea state. This, in turn, has a direct correlation to the noise level. Although sea state can be used to get a general idea of noise level, it is difficult to estimate, thus wind speed is a better parameter to use. The increase in noise level correlated with wind speed can be broken down into a number of processes. Wind blowing over the sea surface generates surface waves which increase surface scatter and flow noise (Isakovich and Kuryanov, 1970). This produces turbulent pressure, which is transmitted to water. The generation of whitecaps is a process that produces hydrostatic noise, which is also transmitted below. Finally, the collapse of the bubbles from the surface waves and whitecaps causes surface cavitation in the air-saturated surface water (Leighton, 1994; Furduev, 1966).

Yet another meteorological source of noise is rain. Clearly, the ambient noise level will be affected to an extent that directly correlates with the rate of rainfall. This effect has been documented (Heindsman et al., 1955; Franz, 1959; Bom, 1969) and has its greatest impact between 1 kHz to 20 kHz.

A source of ambient noise that is especially important in shallow waters is biologics. These sounds may be intermittent or constant depending upon geographic location. The term biologics refers to sounds produced by organisms be they mammals, fish or invertebrates. These sounds are highly varied and have been studied extensively (Tavolga, 1964). Nearly the entire frequency spectrum from 5 Hz to 100 kHz can be affected by sounds of biological origin.

Anthropogenic, or man-made, noise has become the main source of concern as a contributor to elevated ambient noise levels in the oceans in recent years. Many consider it to be the principal source of noise in the oceans (NRDC, 1999). Anthropogenic noise is especially conspicuous in shallow, coastal waters, harbors, and embayments (Scheifele, 1997). Anthropogenic noise can be generated by a wide variety of activities including vessels of all types, construction, military events, offshore oil exploration, scientific undertakings, the use of acoustic harassment devices (AHDs), and dredging operations. Although military and scientific operations have become the focus of attention recently, the dramatic increase in vessel traffic is particularly insidious world wide and particularly in the SBNMS.

Anthropogenic noise, specifically vessel traffic, tends to dominate the noise levels in the 50 to 500 Hz frequency band. This can include traffic as distant from the recording site as 1,000 miles. It can affect frequencies as high as 10 kHz and is especially problematic at frequencies around 100 Hz and has led to the development of very effective propagation models (Burkhalter, 1993). Of all the anthropogenic sources of noise, vessel traffic is the most dynamic, not only due to the number of vessels in operation at any one time but to the size, propulsion configuration, duty cycle and purpose of the vessels.

The advent of super tankers has led to dramatically increased levels in ambient noise. The world merchant fleet accounts for a major portion of the noise field in both the deep ocean and coastal waters. The increase in popularity of eco-tourism has heralded the increase in whale watching fleets with a subsequent seasonal increase in noise within certain sectors of coastal waters including the SBNMS. Commercial and private fishing, including draggers, has also advanced the noise levels in fertile fishing grounds including the Gulf of Maine. A plethora of private and commercial pleasure vessels may cause seasonal increases in noise level, although to a lesser extent than the other sources.

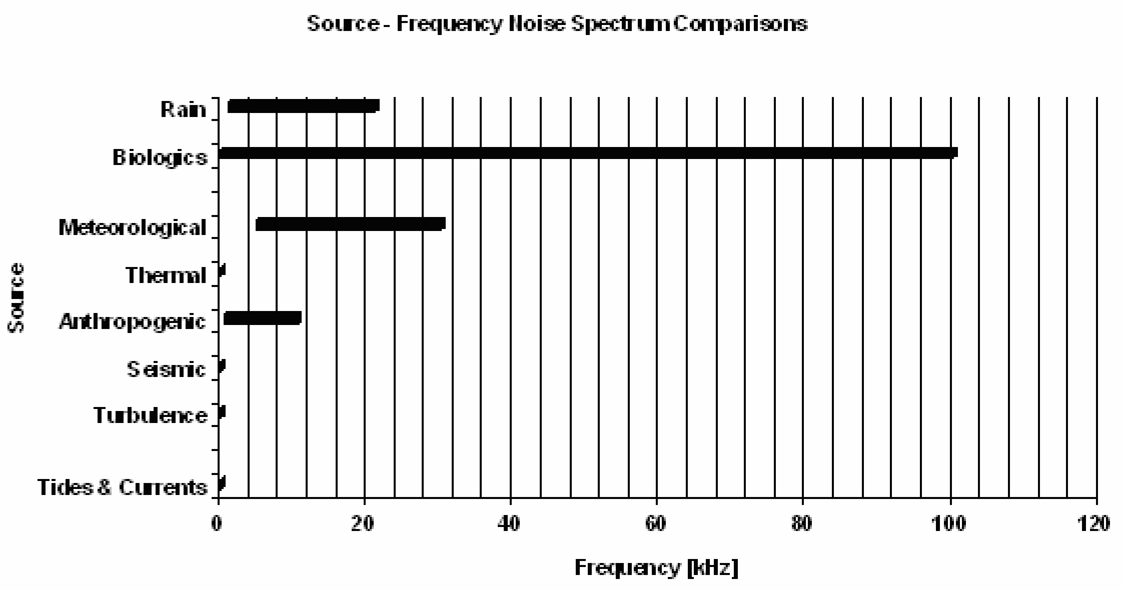

Figure 1. A comparison of noise sources versus frequency ranges of each source comprising ambient noise.

Variability of Ambient Noise

Ambient noise has been shown to be highly variable (Knudsen et al., 1948; Ross, 1976) by as much as 20 dB re 1 *u*Pa per day or even within shorter periods of time as shown by Richardson et al. (1995). Variations in the component sources of ambient noise are partially responsible for the irregularities and constant changes in the overall ambient noise level. Variations in sound transmission conditions are also responsible for these irregularities and changes. The better the propagation conditions the higher the noise level because the sound will attenuate slowly with distance. The sea is an excellent medium for the transmission of sound albeit a very complex one. The many diverse effects on the distribution of underwater sound are due to transmission losses in the medium.

Transmission loss (TL) is defined as the deterioration of an acoustic signal between a source and a receiver. In the case of ambient noise it is taken to be a general weakening of the overall noise level given that ambient noise, in and of itself, is not considered to be a point source but a property of the medium. Transmission loss is a general term representing the sum of spreading, attenuation, and refraction losses (Urick, 1983).

Spreading refers to the weakening of sound as it travels away from a source. With respect to ambient noise, it pertains to that portion of the noise field measured at a distance from one or more of the components such as seismic events, storms, shipping or biologics. Spreading is quantified as a function of geometry with respect to the source. In deep water or within the surface/bottom boundaries of a body of water (referred to as one water-depth) the sound will radiate from the source in all directions as a sphere. This is known as *spherical spreading* and the rate of decay of sound can be calculated outward from the source to a distance of one water-depth as:

$$TL = 20 \log r$$

where TL is taken to be spherical spreading loss and r is the radial distance from the source.

Once the radial distance equal to one water-depth has been reached from the source, the surface and bottom boundaries interfere (since the sound cannot cross the boundaries) and spherical spreading is no longer able to take place. At this point *cylindrical spreading* occurs and the subsequent decay of sound is calculated as:

$$TL = 10 \log r$$

where TL is taken as cylindrical spreading loss and r remains the radial distance from the source as before. Total transmission loss is the sum of spreading, attenuation, and refraction losses.

Attenuation loss refers to the decay of sound, as it travels from the source, due to chemical and physical phenomena. These primarily include absorption and scattering. The calculation of attenuation losses tends to be complex and continues to be extensively studied and modeled. Absorption represents the loss of sound due to transfer of mechanical (acoustic) energy into heat as both mechanical and chemical reactions (Liebermann, 1948). Three specific reactions have been well studied: shear viscosity by Rayleigh (1945), volume viscosity by Mason (1965), and ionic relaxation by Leonard et al. (1949), Schulkin and Marsh (1962), Mellen, et al. (1988a, 1988b) and Scheifele, et al. (1988a, 1988b). A complete synopsis of this research can be found in Urick (1983). An additional physical impact on acoustic attenuation is the sound velocity structure of the water column.

Sound velocity varies as a function of temperature, salinity and pressure at any given location. In general, sound velocity increases with increasing temperature, salinity and depth and can be measured in the field using a CTD (conductivity, temperature, depth) device. Based on these three parameters, a sound velocity profile may be derived. This profile will vary with latitude, season, and time of day. At some locations the acoustic structure of the water column will be stratified as shown in the sound velocity profile, due to temperature, salinity and pressure. Of the three parameters, temperature is most likely to have the greatest effect on stratification of the water column.

Stratification of the water column can cause acoustic zones or sound channels to occur. These may be either deep or shallow. The best known of these is the SOFAR (Sound Fixing And Ranging) channel. The SOFAR channel has a minimum depth of 4,000 feet and is sometimes known as the deep sound channel. At the surface, water is warmed by the sun and mixed by surface wave action to form a surface or mixed layer. Sound is often trapped in this layer creating a surface duct in which sound can travel very well over long distances.

In shallow water where sound is reflected from both the surface and the bottom, a shallow water channel may exist. In this case, acoustic characteristics of the surface and bottom influence the sound field. The sound will propagate over distances at least several times greater than the water depth. This occurs in coastal waters less than 500 feet deep (McLeroy, 1986).

Refraction loss refers to the distortion and instability of sound in relation to boundaries such as the surface and the bottom. Sound can be absorbed or reflected by different bottom substrates. The more porous the sediment, the more sound will be absorbed. On the other hand, noise levels may fluctuate greatly at the sea surface due to reflections from constantly changing wave faces. Ambient noise levels in hard bottom (highly reflective) locations tend to be high (Staal, 1992).

The calculation of transmission loss for practical purposes is complex at best. With respect to ambient noise levels, transmission loss may play less of a role than the source components, however, it is a major factor in determining the propagation of the noise from each of those sources (Staal, 1992; Zakarauskas, 1990). A clear understanding of transmission loss characteristics in the SBNMS is critical toward the enactment of decisions relating to the treatment of noise within its boundaries.

Measurement of Underwater Sound and Surrounding Issues

Acoustic intensity is the fundamental measure of the propagation of sound (Kinsler et al., 1982). Although acoustic intensity is of interest to acousticians and engineers it is not useful in a practical sense. Recall that acoustic intensity infers a measure of power per unit area. For practical reasons (largely due to equipment limitations) it is pressure that is measured and reported. This measurement is known as the Sound Pressure Level, or SPL. Intensity is proportional to the mean squared pressure or rms pressure, therefore, a ratio of pressures is used to quantify and report SPLs.

$$\mathrm{SPL}\ (\mathrm{dB\ re\ 1}\ u\mathrm{Pa}) = 20 \log P/P_{ref}$$

This logarithmic measure of acoustic pressure is known as the decibel (dB).

Quantitative measurements of sound pressure should always include the pressure to Which the measure is being referenced. For underwater measurements the reference pressure is 1 micro Pascal. One issue in acoustics is that researchers are not always conscientious about reporting reference units (Richardson et al., 1995). Using the decibel as a unit of measure of intensity is convenient mathematically and has a number of advantages. It provides a common scale for expressing intensities, it can accommodate a wide range of intensity values (which are normally encountered in acoustics), and it simplifies the mathematics of calculating acoustic measurements. There are however, issues surrounding the use of the decibel when the measurements are intended for use in discussing hearing.

The research and lay communities are more familiar with the measurement of airborne sounds. While the reference pressure for underwater sound is 1 *u*Pa, the reference for airborne sound is 20 *u*Pa (Kinsler et al., 1982; Stevens and Davis, 1983). In addition, airborne sounds measured with respect to hearing are often expressed in reference to human hearing. In these cases they are manipulated or *weighted* to enable medical doctors, audiologists, speech pathologists and acoustical engineers to more closely analyze the sounds with respect to the human "best range of hearing." An "A-weighted" system of measurement is used which de-emphasizes frequencies below 1 kHz and above 6 kHz (Dobie, 1993; Durrant and Lovrinic, 1995). Using the decibel has lead to the mistake of falsely equating airborne noises, in different frequency bands, to one another and worse (more recently) to underwater sounds (NRDC, 1999).

Mathematics and physics do allow for conversion of sound levels from one reference and medium to another (as in the case of air and water). Sound pressure levels (SPLs) are measured in decibels as the ratio of pressures however, it is best to compare intensities because pressure effects between the air and water media are different. Equating intensities may be done as follows:

$$I_a = p^2{}_a / \rho_a c_a \;=\; I_w = p^2{}_w / \rho_w c_w$$

where a represents in-air and w represents in-water. Given, that $\rho_a c_a = 416$ Pa.s/m and that $\rho_w c_w = 1.5 \times 10^6$ Pa.s/m then $p_w = 60$ Pa where p_w and p_a are in Pascals. Now convert to *uPa* by multiplying by 10^6. Therefore,

$$\mathrm{SPL}_a = 20 \log (p_a \times 10^6/20) \text{ and } \mathrm{SPL}_w = 20 \log (p_w \times 10^6)$$

and

$$\mathrm{SPL}_w = \mathrm{SPL}_a + 20 \log (60 \times 20) = \mathrm{SPL}_a + 62 \text{ dB}$$

This accounts for the impedance difference between air and water and gives a true conversion from an in-air to in-water values (Scheifele, 1997). Oceanographers routinely do this however, such comparisons are not meaningful with respect to comparing the impacts on hearing in marine organisms versus terrestrial ones (Smith, 1985). It is also unacceptable if one is comparing the effects of noise on animals with different hearing sensitivities. For an up-to-date treatment of this issue and its relevance to anthropogenic noise see Richardson et al. (1995).

Noise Level Data

It is a matter of debate whether noise levels in the oceans have significantly increased. It seems unquestionable that an increase has occurred over the last 25 years but it is nearly impossible to quantify the change. Few noise-monitoring programs exist. Two programs of interest are in progress: acoustic monitoring of the Saint Lawrence River Estuary in the Tadoussac region of Quebec, Canada, and a summer monitoring program in the Stellwagen Bank National Marine Sanctuary. Both programs take place during peak summer months so that the data are scarce but consistent by site and time of year. The data are taken during the peak whale watching and pleasure boat season. These will be discussed in the following sections.

Upper St. Lawrence River Estuary (Marine Park)

Ambient noise samples have been taken by Scheifele et al. (1997) and Scheifele (1997) at four discrete hours per day at three sites where beluga whales are known to congregate near Tadoussac Harbor, Quebec, Canada. The samples are taken in summer when vessel traffic is at its highest. The traffic consists of ferries, merchant vessels, whale watching vessels, private and government craft. To date, 3,600 samples have been taken and analyzed. Mean noise levels at frequencies of 500 Hz, 1kHz, 10 kHz, and 40 kHz are compared to hearing sensitivity curves for belugas. No such curves exist for any Mysticete species. The selection of sites, all near the confluence of the Saguenay River and the St. Lawrence Estuary, were made in view of their:

1. differing vessel traffic and use patterns causing distinct background noise intensities;
2. regular use by different beluga social groups during the same portion of the summer range (in an effort to reduce confounding factors due to differences among whales of different social groupings and/or of different areas);
3. intrinsic quality of the site's acoustical environments (topography, depth);
4. proximity to one another and, hence, ability to sample them numerous times during a single day. A map is shown on page 14.

Site 1. Saguenay site (48° 07.34'N, 69° 41.40'W) is located approximately 1 km outside of the harbor of Tadoussac at the mouth of the Saguenay fjord. The water depth is 100 m and the area is heavily used by vessel traffic including frequent passage of three Bay St. Catherine-Tadoussac ferries (approximately every 20 minutes), passage of large merchant ships traveling up the estuary, daily whale watching traffic from June to October, and numerous recreational and work vessels. The belugas that pass through this area typically travel in pods of adults accompanied by juveniles (Michaud, 1993). The animals typically feed near this area and pass through en route to sites up the Saguenay River.

Site 2. The Channel Head site (48° 67.83'N, 69° 33.38'W) is located approximately 8 km east of the Saguenay site on the north side of the St. Lawrence estuary. The site (water depth 120 m) is located near an important upwelling and current confluence and is believed to be an important feeding site for belugas, fin whales, and minke whales . Three general types of social groups inhabit these areas: mature males, females and females with young, and young males. This site is used by three social groups of beluga and these groups often travel from site 1 to site 2 or reverse. It is the area of the largest concentration of belugas. The area, located on the Saint Lawrence shipping lane, is also a core area for whale activities. As many as 250 individuals, close to half the population, can be found daily at this site during the summer. Because this area also supports several other whale species (fins, minkes), it represents an area affected by whale watching vessels. It is also affected by the regular passage of merchant vessels.

Site 3. The Alouette site (48° 02.56'N, 69° 40.71'W) is located 8 km west of the Saguenay site on the south side of the St. Lawrence River. The water is shallow (40 m) and subject to moderate tidal currents. This site is less affected by vessel traffic than the other sites with the majority of traffic consisting of the sporadic passage of merchant vessels. The data (thus far) indicate that mean noise levels are nearly the same between years.

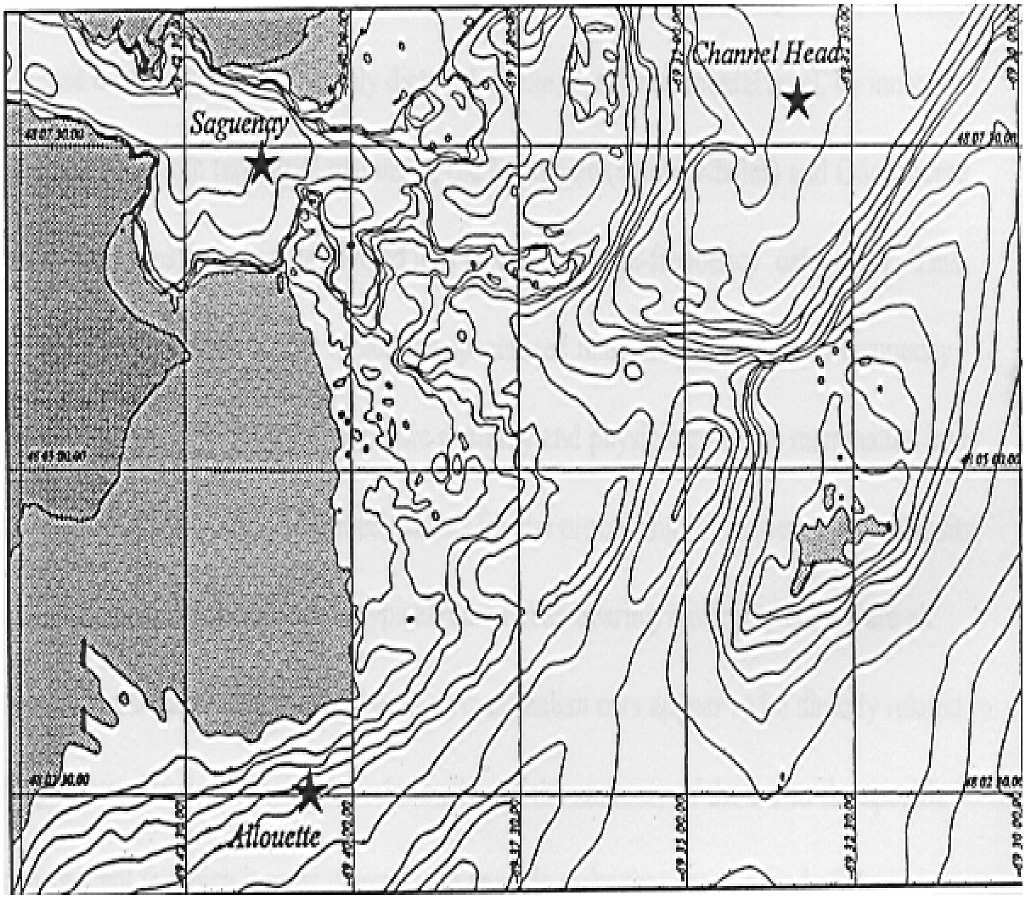

Figure 2. Map of acoustic sample sites in St. Lawrence River Estuary Monitoring Program.

Stellwagen Bank National Marine Sanctuary

Over the last four years, ambient noise samples have been collected at six sites in the SBNMS. Personnel from the National Undersea Research Center and the North Atlantic and Great Lakes Aquanaut Program took these samples in summertime. In addition, one sample was taken by Scheifele in September 1998.

Site designations are shown in Figure 3 and Table 1. These positions are representative of prime whale watching sites that are frequented by humpback, minke, and fin whales in summer. Private and commercial fishing operations take place in the northern sites within the sanctuary. The southern sites are near the shipping lane leading into Boston Harbour.

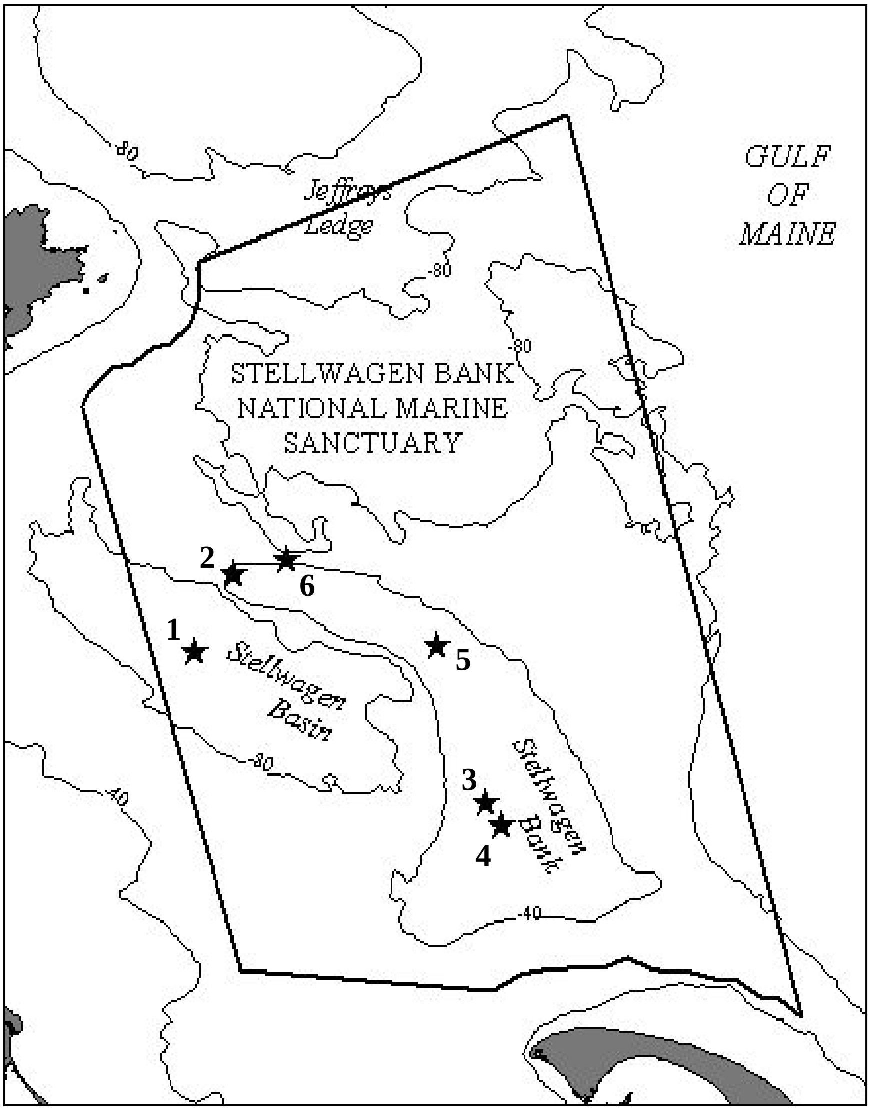

Figure 3. Map of acoustic monitoring sites in the SBNMS.

Table 1. Locations of the SBNMS acoustic monitoring sites.

SITE DESIGNATION	*LATITUDE*	*LONGITUDE*
1	42° 21.74’N	70° 30.32’W
2	42° 25.153’N	70° 28.447’W
3	42° 15.03’ N	70° 16.74’W
4	42° 14.03’N	70° 16.00’W
5	42° 22.00’N	70° 19.00’W
6	42° 25.80’N	70° 26.00’W

Acoustic samples in the St. Lawrence River Estuary are taken at each site at four times of day: 0700, 1000, 1300, and 1600 hours. The 1000 and 1300 hour sample times represent the busiest span of time while the 0700 and 1600 are the quietest times at each end of the day with respect to vessel traffic. Samples are taken in summer, during the peak boating season when the greatest potential for high intensity anthropogenic noise exists. Each hourly sample is taken in three 15-minute duration segments to confirm precision of measurement (mean sound pressure level). Wind speed, sea state, precipitation, and tidal regime are also recorded.

Acoustic samples are taken using an ITC-42A omnidirectional hydrophone and Ithaco amplifier and recorded on a Sony TCD-D8 digital audio tape recorder (DAT) for the 500 Hz, 1 kHz and 10 kHz samples and a Lockheed Store 4D recorder operating at 60 ips is used for the 40 kHz samples. The DAT system has a flat response from 0.5 to 20 kHz and is calibrated with the hydrophone to 1 volt at 1 KHz. Hydrophone depth is 6 m for all samples. The hydrophone has a free-field sensitivity of -188.2 dB for 500 Hz and 1 kHz, -191.1 dB for 10 kHz, and -206.6 dB at 40 kHz. The response is flat to 80 kHz. The recordings are analyzed on a Hewlett-Packard 3562A spectrum analyzer.

As with the St. Lawrence River Estuary, samples at the SBNMS are taken in summer, during the peak boating season with the greatest potential for high intensity anthropogenic noise. Wind speed, sea state, precipitation, and tidal regime are recorded. Bottom type is assessed by 150 m video transects taken with a MaxROV. Sediment samples are also taken and sieved to determine grain size and porosity in an effort to determine basic bottom reflectivity in accordance with Frisk (1980), Dodds (1980), Akal (1980), and Urick, (1983). Contributions of vessel traffic and biologics are extrapolated from radar and the use of maneuvering boards. Acoustic samples are recorded for 50 Hz, 100 Hz, 150 Hz, 500 Hz, 1 kHz, 10 kHz, and 20 KHz samples.

There are preliminary indications that within the St. Lawrence River Estuary the Allouette (site 3) is generally quieter than both the Saguenay (site 1) and Channel Head (site 2) sites. Channel Head tends to be the noisiest site. Noise levels at the Saguenay and Channel Head sites are highest at 1000 and 1300 hours at 500 Hz, 1 KHz, and 10 KHz with the noise levels at 0700 and 1600 hours being similar but of lower intensity. At the other frequencies there are exceptions to the time of peak noise. It can also be seen that for frequencies below 40 KHz the noise levels are highest at the Channel Head site followed by the Saguenay site at 500 Hz and 1 KHz, with the Allouette site being much quieter than either of the first two except at 10 KHz. Table 2 shows mean noise levels (from Scheifele et al., 1999).

Table 2. Mean ambient noise levels at Saint Lawrence River Estuary sites (from Scheifele et al., 1999).

Comparison of Mean Noise levels
at Each Site Across Sample Times of Day

Noise Levels are given at selected frequencies of interest:
500 Hz - Low frequency of Beluga communications and hearing
1 kHz and 10 kHz - Within communications range
40 kHz - Beluga characteristic frequency
Marginal means are shown for comparison across sites and times.

Mean Noise Levels
dB re 1 *u* Pa^2 at 500 Hz

Site		**7:00**	**10:00**	**13:00**	**16:00**	**Marginal Mean**
Saguenay	1	136.5074	143.6337	144.2471	141.6548	**141.5108**
Channel Head	2	135.9819	143.9204	147.3961	142.3131	**142.4029**
Allouette	3	133.4438	140.7552	144.0003	139.9436	**139.5357**
Marginal Mean		**135.311**	**142.7698**	**145.2145**	**141.3038**	

21 dB for 1/3-octave

Mean Noise Levels
dB re 1 uPa^2 at 1 kHz

Site		**7:00**	**10:00**	**13:00**	**16:00**	
Saguenay	1	132.7666	142.3036	145.6135	138.5639	**139.8119**
Channel Head	2	136.6279	142.7716	148.4151	143.2837	**142.7746**
Allouette	3	124.3825	140.561	144.3428	139.7212	**137.2519**
Marginal Mean		**131.259**	**141.8787**	**146.1238**	**140.5229**	

24 dB for 1/3-octave

Mean Noise Levels
dB re 1 uPa^2 at 10 kHz

Site	**7:00**	**10:00**	**13:00**	**16:00**	
Saguenay	102.9867	116.4744	122.182	113.4162	**113.7648**
Channel Head	116.4821	120.6013	121.1932	118.8025	**119.2698**
Allouette	96.8823	103.3884	122.024	103.7126	**106.5018**
Marginal Mean	**105.4504**	**113.488**	**121.7997**	**111.9771**	

34 dB for 1/3-octave

Mean Noise Levels
dB re 1 uPa^2 at 40 kHz

Site	**7:00**	**10:00**	**13:00**	**16:00**	
Saguenay	98.1247	92.1012	99.0566	93.3971	**95.6699**
Channel Head	86.8182	84.8913	91.2197	89.0641	**87.99833**
Allouette	83.3309	93.4091	83.4701	85.1234	**86.33338**
Marginal Mean	**89.4246**	**90.13387**	**91.2488**	**89.19487**	

40 dB for 1/3-octave

The data from the Stellwagen Bank National Marine Sanctuary indicate that mean noise levels are nearly the same between years with the exception of the sites located near the shipping lane. Changes in ambient noise (site raw data) at other sites are largely due to the amount of whale watching activity occurring on the sample dates. However, the mean noise levels are not significantly different from year to year. Table 3 shows a synopsis of the few data points taken to date. The data are taken from a report given in 1999 by the aquanauts of Sage Park School and Scheifele et al., (1999). Proofing and analyses are still in progress and these results are only preliminary. No statistical analyses have been attempted due to paucity of data. Tables 3a, 3b, and 3c show mean noise levels (the mean of 5 samples per site over a single day's time) at frequencies of 50 Hz, 100 Hz and 500 Hz only.

Table 3a. Mean Noise Levels at 50 Hz in the SBNMS by Site (1996 – 1999); (NL in dB re 1uPa/Hz; N = 85); (from Lobach et al. 1999).

SITE	1996	1997	1998	1999
1	72.46	78.57	80.65	68.59
2	85.26	79.20	82.05	74.23
3	87.19	88.19	89.15	86.99
4	88.18	88.21	83.11	83.16
5	80.28	91.23	90.79	80.26
6	95.34	93.16	91.33	91.97

Table 3b. Mean Noise Levels at 100 Hz in the SBNMS by Site (1996 – 1999); (NL in dB re 1uPa/Hz; N = 85); (from Lobach et al. 1999).

SITE	1996	1997	1998	1999
1	60.46	50.00	53.12	53.26
2	43.00	58.45	55.16	56.00
3	50.19	57.78	51.00	57.187
4	98.58	79.49	92.02	95.97
5	69.32	68.15	67.46	68.36
6	98.54	90.65	91.31	80.44

Table 3c. Mean Noise Levels at 500 Hz in the SBNMS by Site (1996 – 1999); (NL in dB re 1uPa/Hz; N = 85); (from Lobach et al. 1999).

SITE	1996	1997	1998	1999
1	52.11	50.01	50.00	51.85
2	48.00	58.99	52.00	56.20
3	50.25	55.06	49.99	55.37
4	78.79	72.33	72.05	75.65
5	60.00	68.42	65.00	65.87
6	78.99	80.22	71.15	80.64

Vessel Traffic in the SBNMS

In addition to the types of vessels and the shear number of them traversing the SBNMS, the propulsion configuration can make a great contribution to noise level and frequencies introduced into the water. The propulsion plant is primarily responsible for the frequency signature of any given vessel, but most of the additional noise comes from the "screw-blade configuration" and how the ship is operated. Most merchant vessels run with either a "single-five" [blades] or a "twin-three or five" configuration. Their presence and configuration are readily apparent to even the most junior sonar operator. Ship captains tend to run at 9 – 12 knots. At these speeds cavitation is the norm. Cavitation of the ship's propeller can yield an enormous amount of noise. This has been well known to military sonar operators since World War II but has only recently been studied more closely (Leighton, 1994). Merchant vessels typically cavitate especially when they are inbound and fully loaded. Outbound vessels are usually light and high and some 1/3 of the propeller surface can be seen out of the water causing surface bubbles and a large wake. Cavitation has theoretically been alleviated with the advent of vessels using jet-wash propulsion plants, however, the problem of cavitation bubbles still exists, although the degree is uncertain.

Although vessels in the shipping lane (mostly commercial) account for most of the distant or near field noise in the SBNMS there are some seasonal and transient contributions of significance. Fishing activities, specifically dragging, have caused some recordings to be high. These "events" are not normally consistent across samples. Another significant contribution at nearly all sample sites in summer is whale-watching activity. Although the whale watching activity in the SBNMS is not nearly as intense as in the St. Lawrence River Estuary it still has significant impacts on local noise levels during the season. A number of research groups, such as the Cetacean Research Unit and even the SBNMS personnel and Auster and Trimarchi (pers. comm.) have been observing cetacean behavior in the presence of vessel traffic yet it remains uncertain what, if any, impact the present noise levels may be having on the whale population of the bank. Preliminary analyses were conducted by Lobach et al. (1999) to compare the noise levels to the hearing sensitivities of the Harbour Porpoise (*Phocoena phocoena*) (Au, 1993) and Pilot Whale (*Globicephala melaena*) (Fay, 1988; Miller et al., 1998) do not indicate any adverse probabilities save for potential masking effects.

Twin-hulled, jet-propelled vessels are now being introduced for use as ferries and whale watch vessels. They are fast, so they are economical in the sense that they reach their destination sooner, allowing for more trips per day to be made. Owners and shipbuilders champion their cause under the guise of the ship not having a propeller. To date, little quantitative research has been done on the acoustics of such a vessel, although it has been inferred that they are actually quieter than the "traditional" propeller driven vessel. The issue remains as to whether they can be heard by marine mammals that are at the surface in enough time for the animal (or the vessel captain) to perform evasive maneuvers. The issue is demonstrated by a number of documented ship strikes of whales (Measures, 1998).

Current Issues Regarding Noise in the SBNMS

There is a distinct need to develop and conduct a formal acoustic monitoring plan within the SBNMS. Presently only NURC NA&GL at the University of Connecticut and Woods Hole Oceanographic Institution (WHOI) are considering plans for long-term acoustic monitoring including the use of buoys, arrays, and/or Autonomous Underwater Vehicles (AUV). Specifically, quantifiable temporal ambient noise data is needed to characterize the acoustic environments in all sectors of the Bank and to determine what contribution the shipping lane is making. Transmission loss research would also be useful in determining the characteristics of the acoustic environment, especially in sectors most frequented by whales. Likewise, more research into bottom interactions is needed to add to recent studies such as that of Lyons and Abraham (1999). Ship signature and source levels of vessels routinely operating within the confines of the sanctuary would be helpful especially in the case of jet-wash vessels.

The SBNMS is an excellent location to continue bioacoustic and psychoacoustic (behavioural) research especially with regard to Mysticete species and the endangered Northern Right Whale (*Eubalaena glacialis*). This research should include marine mammal hearing (anatomical and audiological) research, marine mammal tracking and behavioral research. The objectives of these studies should include, but not be limited to, assessment of the actual exposure of the whales to anthropogenic noise in their natural habitat on a regular basis in the SBNMS, evaluation of the observable impacts of such exposure in terms of anatomical, histopathological and behavioural markers, and to propose adequate measures for managing and protecting other marine mammals in similar situations. Research regarding this topic has not, to date, taken such a multi-disciplinary approach, consequently, there is much disagreement regarding the effects of noise pollution on whale hearing, especially when viewed from a physics/engineering versus biology versus psychophysical viewpoint (Mercado and Frazer, 1999). More research is needed on equating airborne hearing and underwater noise levels. A consensus must be reached regarding consistent measurement techniques and bioacoustic standards with respect to marine mammals.

Management

The best that can be expected of current management is a recognition that excessive noise can and will present a problem to many species of organisms within the sanctuary and a commitment to exploring the extent to which this problem exists in the SBNMS. Next, there is a need to monitor the situation to determine whether the problem is chronic and of an increasing nature (elevating noise levels). Finally, decisions as to how to cope with or alleviate such potentially insidious problem must be made. This may even require collaboration at a federal level in the form or reforming the Marine Mammal Protection Act.

In collaboration with other organizations that are now pursuing similar issues, such as Parks Canada and the Department of Fisheries and Oceans in Canada (Bailey and Zinger, 1996), information and ideas should be pooled to expedite the processes mentioned above. These represent minimum measures. More global measures that may be of interest may be found in the report by the National Resources Defense Council (1999).

Richardson et al. (1986) described the assessment of the potential effects of noise on marine mammals as being based on specific zones of influence. These consist of four criteria: (1) the zone of audibility, (2) the zone of responsiveness within which an animal reacts to the sound, (3) a zone of masking within which the noise levels can interfere with other sounds or even whale signals, and (4) the zone of hearing loss or discomfort. This should be assessed within the context of vessel operating zones within the SBNMS especially with respect to whale watching. Previous studies of noise effects on whales have largely been based on behavior. When considering the relationship of noise to acoustic behavior, flight response of the animal must also be considered. Each animal will respond within some flight distance when it perceives a change in the environment (Hediger, 1964). The flight distance is a specific amount of space surrounding an animal in which the animal feels at rest. When a perceived source of danger breaches the border of the flight distance, the animal elicits some behavioral response. This needs to be revisited with respect to management issues relating to marine mammal behavior around vessels and the shipping lane in the Stellwagen Bank National Marine Sanctuary.

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