UNTREATED MUNICIPAL SEWAGE DISCHARGE IN VICTORIA BIGHT, BRITISH COLUMBIA, CANADA: AN INVESTIGATION OF SEDIMENT METAL CONTAMINATION AND IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT

by

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ACRONYMS

AET	Apparent Effects Threshold
ANZECC	Australia and New Zealand Environment and Conservation Council
BDL	Below Detection Limit
CCME	Canadian Council of Ministers of the Environment
Cr	Chromium
CRD	Capital Regional District
Cu	Copper
(D)GPS	(Differential) Global Positioning System
EC	Environment Canada
ERL	Effects Range Low
ERM	Effect Range Median
ESRI	Environmental Systems Research Institute
FAA	Flame Atomic Absorption
GIS	Geographic Information System
HK	Hong Kong
ISQG	Interim Sediment Quality Guideline
ISQV	Interim Sediment Quality Value
KMO	Kaiser-Meyer-Olkin
LEL	Lowest Effect Level
LWMP	Liquid Waste Management Plan
MET	Minimum Effect Threshold
MMAG	Marine Monitoring Advisory Group
MT	Metallothionein
NAD 83	North American Datum 1983
Ni	Nickel
NOAA	National Oceanic and Atmospheric Administration
PC	Principal Component
PCA	Principal Component Analysis
PEC	Probable Effect Concentration
PEL	Probable Effect Level
RPD	Relative Percent Difference
SD	Sustainable Development
SEL	Severe Effect Level
SLFD	Sierra Legal Defence Fund
SQG	Sediment Quality Guidelines
SQO	Sediment Quality Objectives
TEC	Threshold Effect Concentration
TEL	Threshold Effect Level
TET	Toxic Effect Threshold
US EPA	United States Environmental Protection Agency
UTM	Universal Transverse Mercator
WDOE	Washington Department of Ecology
Zn	Zinc

ABSTRACT

The city of Victoria (British Columbia, Canada) and its surrounding environs, governed by the Capital Regional District (CRD), discharge untreated municipal sewage into the Strait of Juan de Fuca. This method of sewage disposal has been, and is, the source of heated debate between politicians, environmentalists and scientists alike. The CRD defends its current liquid waste management program based on the findings of a few reports, and periodical monitoring that suggest the current system has no serious adverse affect on the receiving environment (beyond the immediate area of the outfall). Some members of the scientific community have questioned the validity of the science behind the reports. Given the highly dynamic receiving environment, the geographical extent of past research and current monitoring is insufficient.

Based on empirical data, this research addresses knowledge gaps regarding the distribution and level of Cr, Cu and Zn contamination in the sediments of Victoria Bight. The current liquid waste management plan (LWMP) is also scrutinized from a sustainable development point of view. Varying levels of sediment contamination were identified throughout the study area. Levels were consistently elevated in three areas. The northern section of Victoria Bight, near Royal Roads, is the largest affected area. Two smaller areas of elevated contaminant levels are located immediately south of Albert Head, and at the southern boundary of the study area, adjacent to William Head. Study results indicate that the Macaulay Point outfall is probably responsible for the majority of sediment contamination in Victoria Bight. The current LWMP is not sustainable, particularly regarding protection of biodiversity, and the precautionary principle. Results from this study provide a broader understanding of the condition of the sediments in the receiving environment. The knowledge gained can be used to shape sustainable waste management policy.

1.0 Introduction

The Greater Victoria area (British Columbia, Canada), governed by the Capital Regional District (CRD) discharges approximately 120,000m^3 of untreated municipal sewage per day into the Juan de Fuca Strait through two submarine outfalls located at the southern tip of Vancouver Island (Figure 1) (CRD, 2000). The aim of the research described in this paper is to determine the spatial distribution and concentration of selected heavy metals in surface sediments in Victoria Bight; and to determine if the submarine outfalls are the likely sources of those metals. This research is the first study to conduct a thorough sediment survey encompassing all of Victoria Bight to determine the potential impacts of the outfalls on sediments in the receiving environment. The research findings are also used to assess the CRD's current Liquid Waste Management Plan (LWMP), and the implications for the receiving environment from a sustainable development perspective.

1.1 CRD Outfalls

The CRD sewage outfalls serve a population of approximately 322,000 (SLDF, 1999). The outfall pipes extend into Victoria Bight from Macaulay Point and Clover Point. The Macaulay Point outfall is 900mm in diameter and extends 1.7 kilometres into Victoria Bight terminating in 60m of water. The Macaulay Point outfall serves the municipalities of Colwood, Esquimalt, View Royal, Langford, Vic West and most of Saanich. Leachate from the Hartland landfill is also pumped out through the Macaulay Point outfall. In 1999, the average daily discharge from Macaulay Point was 48,500m^3. The Clover Point outfall is 1100mm in diameter and extends 1.1 kilometres into Victoria Bight where it terminates in 67m of water. The Clover Point outfall serves Victoria, Oak Bay and Cadboro Bay. The 1999 daily discharge average was 71,800m^3. The only treatment prior to discharge from either outfall is screening through a 6mm mesh to remove large particles. Screenings are removed twice a week and disposed of at the Hartland Landfill (CRD, 2000). The effluent discharged into the Strait is the combined liquid waste from individual households, industries, businesses, institutions, commercial establishments and landfill leachate (CRD, 2000; SLDF, 1999).

Figure 1. Study Area

1.2 Heavy Metals

The untreated sewage contains a wide variety of chemicals and contaminants that are potentially harmful to the receiving environment. Some of the contaminants found in untreated sewage are: polycyclic aromatic hydrocarbons (PAHs), phenols, chlorinated hydrocarbons, pathogens, polychlorinated biphenyls (PCBs) and heavy metals (SLDF, 1999). This study focuses on heavy metal contamination. The potential harm caused by heavy metals in the environment has been well documented. Negative effects observed in a number of organisms range from behavioural changes to death (Rainbow and Furness, 1990; Langston, 1990; EVS, 1992b; Anderlini and Wear, 1992; Power and Chapman, 1992). Also, metals are a good indicator of anthropogenic, as opposed to natural, sources of contamination (Birch, 1996; Luoma, 1990; Paetzel et al., 2002; Chague-Goff and Rosen, 2001; Zhang et al., 2001; Sutherland, 2000; Emmerson et al., 1997; Simeonov et al., 2000).

The three metals analyzed for this study are Chromium (Cr), Copper (Cu) and Zinc (Zn). The CRD and the U.S. EPA have identified all three metals as priority pollutants (CRD, 2000; Langston, 1990). Of the three metals analyzed, Cu is of prime importance. Past research indicates that Cu is potentially the most significant marine environmental pollutant. Studies have shown that Cu may be toxic to biota at levels only marginally above background levels (Langston, 1990). Also, of particular relevance to this study, Cu levels in sediments are monitored by the Marine Monitoring Advisory Group (MMAG), an independent body that monitors and advises the CRD on issues related to the CRD's LWMP. Sediment Cu levels are one of the MMAG's 'trigger' mechanisms that are meant to invoke re-evaluation of the current level of sewage treatment (CRD, 2000; Bright, D. Pers. Comm., 2002). All three metals studied for this project are routinely analyzed in the determination of sediment contamination (Paetzel et al., 2002; Sanudo-Wilhelmy et al., 2002; Spencer, 2002; Birch et al., 2001; Chague-Goff and Rosen, 2001; Zhang et al., 2001; Simeonov et al., 2000; Sutherland, 2000; Ruiz et al., 1998; Emmerson et al., 1997; Padmalal et al., 1997; Birch, 1996; Huang et al., 1994; Turner and Millward, 1994; EVS, 1992b).

1.3 Sediments

Sediments are a matrix of materials usually found beneath bodies of water. They are composed of inorganic and organic particles made up of shell and rock fragments, minerals, atmospheric fall-out and eroded soil and waste particles (Power and Chapman, 1992). Through both natural (e.g. watershed drainage) and un-natural (e.g. sewage discharge) processes, sediments are ultimately the terminus for both natural and anthropogenic materials, for which reason they tend to be susceptible to contamination (Power and Chapman, 1992). In broad terms, sediments can be classified as either coarse or fine. The coarse fraction (greater than 62µm) is comprised mainly of stable, non-cohesive inorganic silicate materials. Generally, coarse sediments are not associated with chemical contamination (Power and Chapman, 1992). The fine fraction (less than 62µm) consists of particles that have large surface area to volume ratios. The surfaces of fine particles often carry an electric charge, making fine sediments more chemically and biologically reactive than coarse sediments, thereby increasing the likelihood of sorption and desorption (Power and Chapman, 1992). As a consequence of the physio-chemical properties of fine particles, chemical contamination is usually associated with fine sediments, a characteristic frequently associated with depositional areas (Zhang et al., 2001; Padmalal et al., 1997; Power and Chapman, 1992, McLaren and Little, 1987; Young et al., 1985).

The reactive nature of fine particles has serious implications for the fate and transport of heavy metals in the marine environment. Metals are highly reactive with particles, and the combined reactivity of fine sediments and heavy metals means that, through adsorption, sediments trap large portions of incoming contaminants. Sediment metal concentrations often exceed those in overlying water by several orders of magnitude (Langston, 1990). As a contaminant sink, sediments are critically important as a direct source of metal toxins for benthic organisms in marine environments (Luoma, 1990; Langston, 1990). In regard to environmental monitoring, metal concentrations in sediments are useful in the assessment of anthropogenic inputs of metals. As such, sediments provide a good indication of the effects of sewage on receiving environments (Langston, 1990; Taylor et al., 1998).

1.4 Sustainable Development

In addition to determining the level and distribution of sediment metal contamination, this study critically evaluates the science and sediment quality guidelines, used by the CRD, to assess the state of the receiving environment from a sustainable development perspective. Actions, activities and systems must adhere to a number of fundamental principles that underlie sustainable development, to be considered sustainable. The protection and preservation of biodiversity, and the precautionary principle are two of the paradigms underlying sustainable development that are particularly relevant to the issue of sewage disposal to the marine environment. Sediments are a key component of the marine environment. The organisms that live in and depend on sediments make up a large portion of the foundation of the marine food chain (Power and Chapman, 1992). Numerous studies have demonstrated that toxic sediments have been the cause of reductions in, or alterations to, sedimentary organisms (EVS, 1992b; Anderlini and Wear, 1992; Langston, 1990). Some of the negative impacts these changes to the marine environment have had on higher trophic levels (including humans) have been documented. Nevertheless, the long-term effects remain uncertain, and future generations may be subject to unknown risks (Luoma, 1990).

> *The loss of a keystone species will eventually lead to a multitude of linked extinctions through a ripple effect that spreads throughout the ecosystem.*
>
> *Meyers, N. (as cited in Dale, 2001)*

1.5 Significance of Research

There have been a limited number of studies regarding the impact of the CRD outfalls on the sediments in the receiving environment. With the exception of this study, all previous investigations have been largely confined within a 2km radius of the outfalls. The most comprehensive study to date is based on 25 sample sites. Of these sites; 12 are within a 1.6km radius of Macaulay Point, 1 site is located 3km southwest of Macaulay Point, 9 samples are within 1.2km of Clover Point (from which no sediment was successfully retrieved), and the remaining 3 samples are reference sites located in Parry Bay, approximately 10km southwest of the Macaulay Point outfall (Figure 2). The limited areal extent of previous studies does not satisfactorily address one of the principles of contaminated sediment transport and deposition. It is well understood that in coastal zones, regardless of the point of introduction, fine particles seek preferred zones of deposition. In cases of continuous contaminant input, the source of input is likely to be responsible for consistent contamination at the input site as well as secondary contamination in depositional areas. Proper surveillance or monitoring studies must be designed to account for the physical transport of sediments and the resultant redistribution of their associated contaminants (Luoma, 1990; McLaren and Little, 1987; Young et al., 1985).

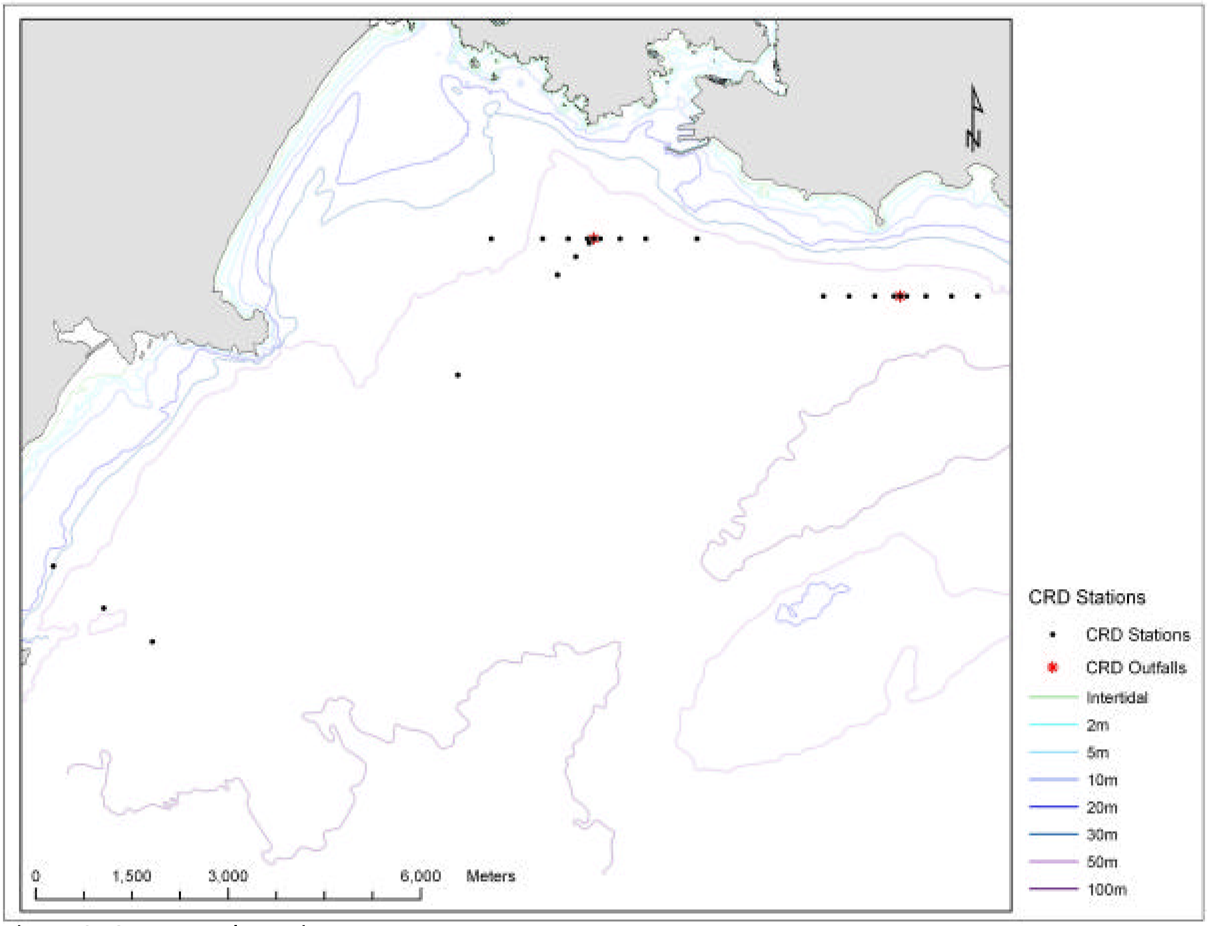


Figure 2. CRD sample stations

Sampling for this study was designed to accommodate for both the potential for primary contamination at the sewage disposal site and secondary contamination related to sediment transport and deposition. The areal coverage of the study is defined by the geographic extent of Victoria Bight (Figure 1). The sample design was based on a hexagonal grid with a 500m resolution. A total of 582 samples sites were initially identified (Figure 3).

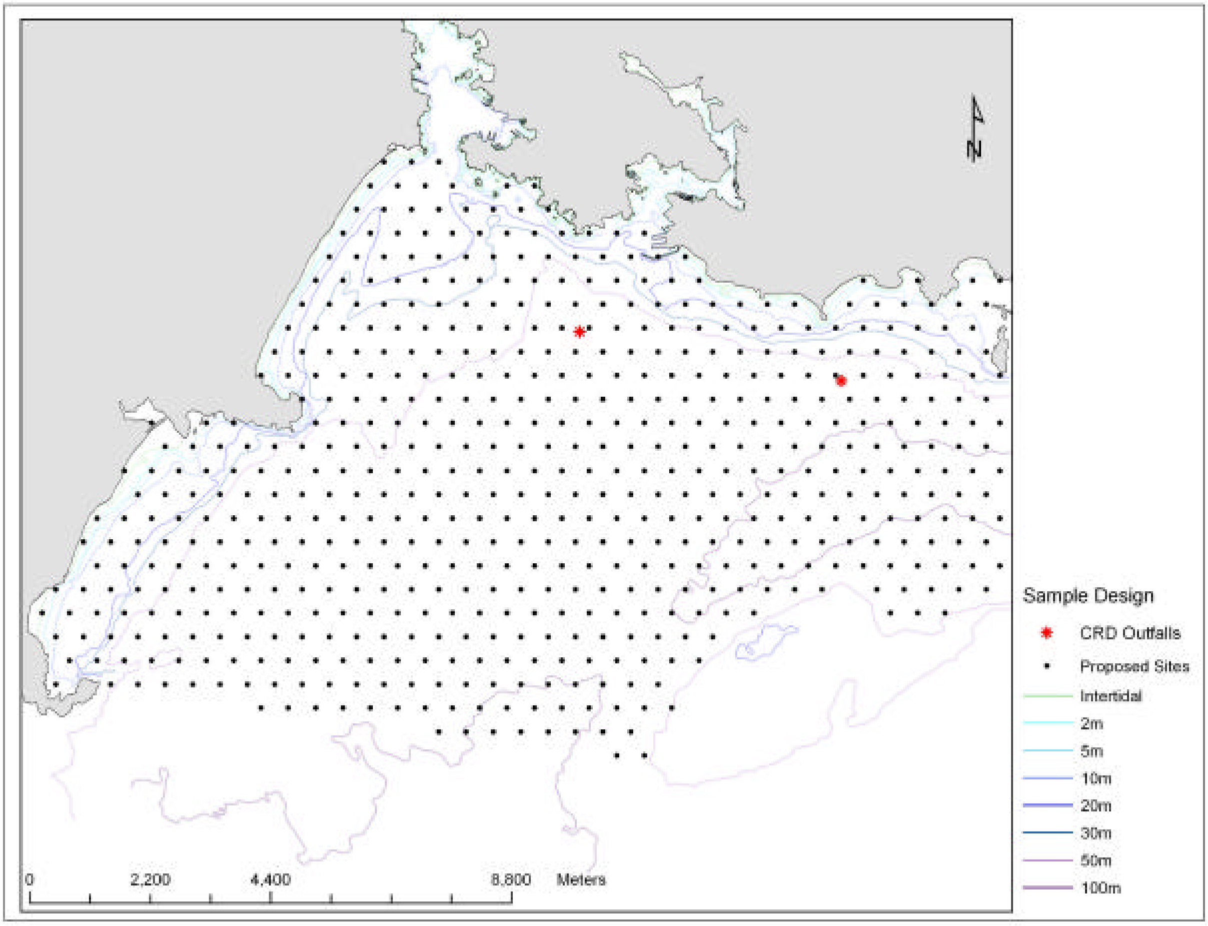


Figure 3. Sample design

Based on sediment grain-size analyses and the propensity for metals' association with fine particles, 360 sample sites were selected as sites potentially suited for metals analysis of Cr, Cu and Zn (Figure 4). The research findings discussed in this paper fill some of the knowledge gaps regarding the distribution and levels of sediment metal contamination, resulting from the discharge of untreated sewage, in Victoria Bight. Furthermore, prior to this study, new scientific data have not been used to evaluate critically the science and guidelines used to justify the current LWMP from a sustainable development perspective. Thus, the research findings are significant at a number of levels. The new data provide an unprecedented sediment database for Victoria Bight. At a basic knowledge level, the study provides a broader understanding of sediment types and metal contamination in the receiving environment. This information is an integral component of rational coastal zone management practices. At a decision making level, the scientific findings will allow decision makers to make the best use of the limited resources at their disposal. Finally, the information acquired will allow the CRD to re-evaluate the current LWMP from a sustainable development perspective. Doing so would ensure that sound, defendable and most importantly, sustainable liquid waste management practices are employed by the CRD.

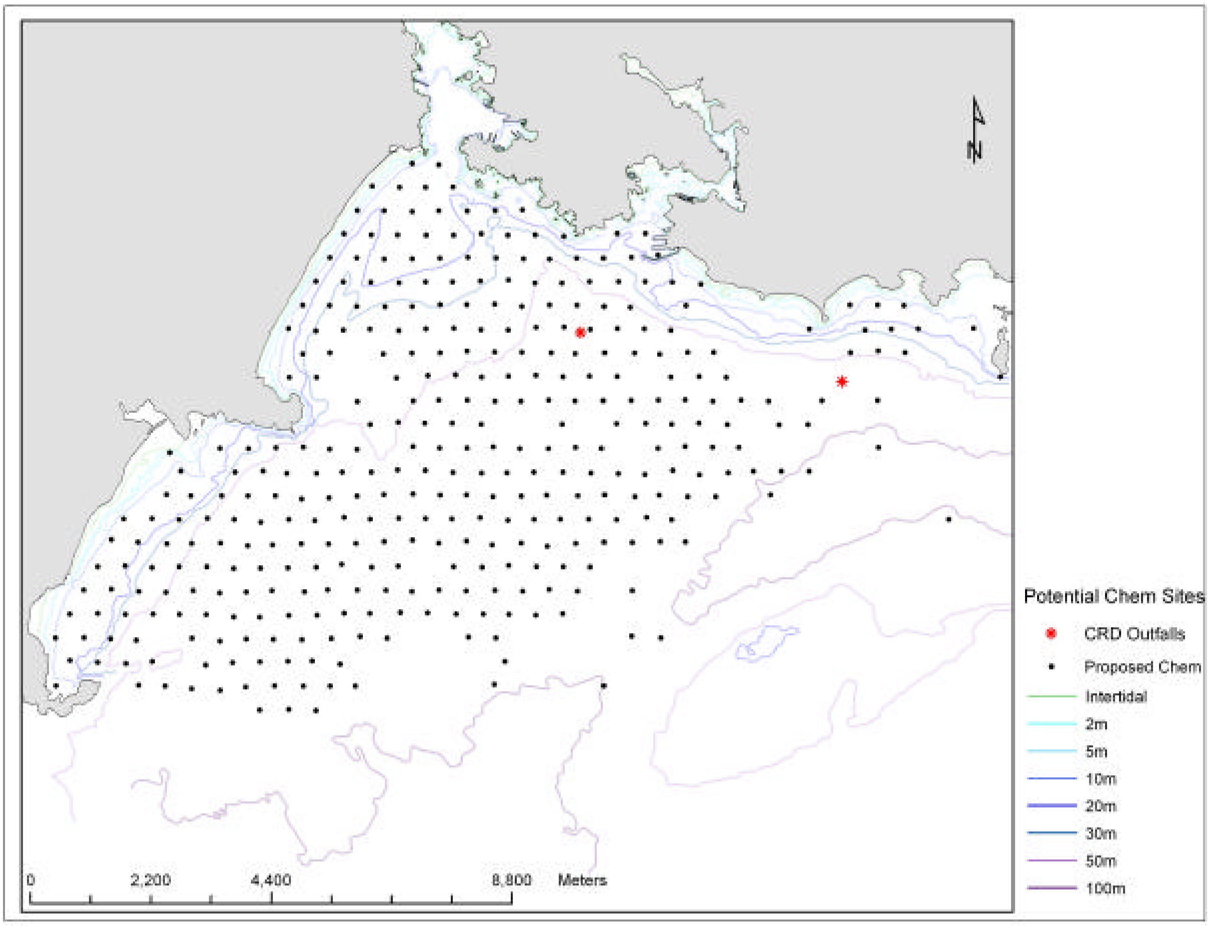


Figure 4. Potential chemical analysis sites

2.0 Literature Review

2.1 Opposing Views

The CRD's current LWMP, and the impact of the sewage outfalls on the receiving environment, has been a continuous source of debate for scientists, environmentalists, citizens and politicians from all levels of government. The sewage issue is not only an environmental one, but rather has significant economic and political implications, and this is evident in scientific literature, outspoken environmental groups, and popular journalism. As with all contentious issues, there are two sides to the Victoria sewage debate. Proponents of the status quo argue that the assimilative capabilities of the receiving environment are more than adequate in terms of handling the volume of waste discharged. They maintain that the receiving environment is highly dynamic, and that rapid dilution of waste prevents any build-up of contaminants (Palmer, 1999; Taylor et al., 1998; Rogers, 1995; EVS, 1992b).

Those who oppose the status quo argue that contamination from the outfalls is responsible for the closure of a shellfish fishery in the Juan de Fuca Strait, and that the CRD is in contravention of both the *Canadian Fisheries Act*, and conditions stipulated in the CRD's provincial waste discharge permits. Opponents also claim that negative impacts to the receiving environment are occurring well beyond the outfalls themselves, and that the science behind the decision-making is suspect (Cleverley, 2001; Connelly, 1999; SLDF, 1999; Werring, 1999). The published literature surrounding the CRD's LWMP reflects both sides of the waste issue. The published literature put forth by proponents of the current LWMP is comprised of technical and scientific reports along with peer-reviewed journal articles. There are also a number of informative documents made available to the public, by the CRD, regarding the LWMP. In contrast, the majority of the published literature by critics of the CRD's LWMP is in the form of newspaper articles, media-releases and reports from environmental groups.

2.2 The Science

In 1992, in an attempt to reduce the amount of uncertainty regarding the impact of the outfalls, and placate opponents of the LWMP, the CRD commissioned EVS Consultants to conduct an environmental assessment on the effects of untreated municipal sewage on the sediments in the receiving environment. The ensuing report: *Sediment and Related Investigations off the Macaulay and Clover Point Sewage Outfalls* (EVS, 1992b) has been the main source of scientific information for the public and decision-makers alike. The report and its findings have also been the basis for a number of related journal articles (Palmer 1999; Taylor et al., 1998; Rogers, 1995), all of which were authored by either EVS or CRD personnel. The CRD have used the findings of the EVS report for continued defence of the current LWMP.

The environmental assessment carried out by EVS was conducted in two phases. An initial study was undertaken to evaluate qualitatively the condition of the receiving environment (EVS, 1992a). An underwater camera was used to obtain a number of sediment profile images in the vicinity of the outfalls. These images were used to identify sites most likely to be impacted from the sewage, and consequently the sites that would best warrant quantitative analysis and monitoring (EVS, 1992a). With the exception of potential reference sites in Parry Bay and east of Trial Islands, the area surveyed for outfall monitoring stations was confined to within a 2km radius of each outfall. While the area investigated addresses the issue of primary contamination at the site of discharge, it fails to address the issue of secondary contamination associated with sediment transport. As noted in Section 1.5, regardless of the point of introduction, fine particles and associated contaminants seek preferred zones of deposition. Therefore, depositional areas prone to contaminant build-up must be accounted for in the design of effective surveillance and monitoring programs (Luoma, 1990; McLaren and Little, 1987; Young et al., 1985).

Having identified monitoring sites, EVS proceeded with the second phase of the assessment. Sediment samples were collected from Macaulay Point and Parry Bay stations. Mussels (*Modiolus*) were collected for tissue analysis, from the Clover Point stations, where no sediment could be retrieved (Figure 2). EVS conducted thorough analyses of the data they had collected. Rigorous testing for organic and inorganic contaminants, along with toxicity testing was carried out. The report concluded that the sewage had minimal impact on the receiving environment, and that those impacts are confined to within 400m of the Macaulay Point outfall (Taylor et al., 1998; EVS, 1992b).

The findings of the report are questionable for a number of reasons. The initial problem of failing to address areas of secondary contamination was not rectified in the final study. This is somewhat surprising considering the main argument used by proponents to defend the current LWMP; namely, that the receiving environment is highly dynamic and rapid dilution of the effluent prevents contamination build-up. This is especially evident near the Clover Point outfall where strong currents have left a scoured seabed more or less devoid of sediment. Supporters of the status quo also note that the effluent, which is comprised mainly of fresh water, is more buoyant than the receiving waters. Therefore, the effluent rises in the water column and is rapidly dispersed before particulates and associated contaminants settle into the sediments. Related to this, a drift card study by Crone et al. (1998) indicated that 60% of floatables from the outfalls remained in Victoria Bight due to tidal currents and eddies. These particular characteristics suggest that secondary contamination could potentially be more significant than primary contamination at the source. Despite this, the CRD's monitoring sites are concentrated around the outfalls themselves, and the area within 100m of each outfall is considered the 'worst case scenario' (Taylor et al., 1998; EVS, 1992b).

Review of the EVS report leads to other concerns particularly regarding the sample design used by EVS to conduct the environmental assessment. Three sites in Parry Bay were used as reference stations (Figure 2). Modelling by Seaconsult in 1992, however, concluded that deposition from the outfalls is occurring in Parry Bay and south of William Head (EVS, 1992b). Therefore, although reference sites are normally meant to provide an example of an undisturbed case, those selected by EVS are likely contaminated, and consequently are unsuitable (Werring, J. Pers. Comm., 2003). Furthermore, the EVS sample design was based on an understanding of major currents, transport modelling and underwater photography (EVS, 1992b). There is a line of sample stations extending southwest from the Macaulay Point outfall, however there are no samples extending southeast from the outfall, the direction of the most frequent subsurface current direction (Figure 7a). Sediment transport studies conducted by GeoSea Consulting further support this, indicating sediment transport in a southeastern direction from the outfall (GeoSea, 1999).

Another issue to consider when interpreting the findings of the EVS report, and statements made by the CRD regarding the level and extent of impacts, are the sediment quality guidelines (SQGs) by which the sediments are being evaluated. The term ‘contamination’ is highly subjective. Understanding how it has been defined in any particular situation is crucial in order to put statements regarding contamination into context. The sediment quality guidelines currently used by the CRD are based on Apparent Effects Threshold (AET) values originally developed for Puget Sound. These SQGs were selected because of Victoria’s proximity to Puget Sound, which raises some questions in terms of their validity (EVS, 1992b). AETs are empirically based and are site specific (Burton, 2002). Although Victoria is close to Puget Sound, the two environments are completely different. Puget Sound is a dead-end fiord with a number of major sediment input sources such as rivers, streams and coastal erosion. The area is not very dynamic and large depositional areas are expected. Alternatively Victoria Bight is subject to the full tides and currents of the Pacific Ocean, and is generally a much more dynamic environment (McLaren, P. Pers. Comm., 2003). Therefore, it is unlikely that SQGs developed for Puget Sound are a good measure of sediment quality in Victoria Bight. Furthermore, AETs are defined as the amount of contaminant in sediments above which a particular effect has always been observed. In the case of Puget Sound, the effects tested for were acute or chronic adverse effects on aquatic organisms, or a significant risk to human health (Ginn and Pastorok, 1992). A concern with AETs is that they are often under-protective since they are founded on levels that “always” have an effect (Burton, 2002). The SQGs currently used by the CRD are consistently higher than those developed by British Columbia Environment, Environment Canada, and the Canadian Council of Ministers of the Environment.

2.3 Other Issues

Review of the published literature regarding the Victoria sewage outfalls reveals a number of issues which must be considered when evaluating the situation. As noted above, all peer reviewed journal articles are based on the EVS report, and written by CRD or EVS personnel. As a result, any shortcomings from the EVS report, or biases from supporters of the status quo, have been propagated throughout the literature, and on to decision-makers and the public.

Negative impacts related to the outfalls are consistently downplayed in the EVS report and in any CRD literature regarding the outfalls. Impacts are consistently described as 'minimal', and the potential importance of sub-lethal effects are downplayed. For example, the report notes that biomass is greatly increased around the outfalls, specifically the presence of annelids, yet biodiversity is decreased. The report fails to mention that this scenario may be an indication of a highly stressed or polluted environment (Langston, 1990). The report also notes that organisms around the outfall do not appear affected, yet fails to discuss that the community structure is formed of tolerant species, and not those normally found in undisturbed environments similar to Victoria Bight (Anderlini and Wear, 1992).

Politics and economics are obviously an influence on the sewage debate. In 1992, the CRD held a referendum to determine what level of treatment should be applied to Victoria's sewage. The scientific information provided to the public was based on the EVS report and, according to information in a prosecution brief by the SLDF, the CRD greatly exaggerated the cost of implementing sewage treatment. Essentially, the public was told that the sewage is not a problem, and that treating it is prohibitively expensive. As a result, the public voted to continue with the status quo (Werring and Chapman, 1999).

3.0 Study Area: Physical Setting

Victoria, British Columbia, is a coastal city located at the southern tip of Vancouver Island. The coastline of the Greater Victoria area forms a natural bend, resulting in an open bay or bight – in this case, Victoria Bight. The geographic extent of Victoria Bight delineates the study area for the research discussed in this paper. Victoria Bight is part of a larger body of water called the Juan de Fuca Strait. The Juan de Fuca Strait is a long submarine valley that is the main body of water connecting the Pacific Ocean and the inner shelf waters of southern British Columbia (Figure 1) (Thomson, 1981).

3.1 Quaternary Geology

Juan de Fuca Strait was occupied by continental ice on a number of occasions during the Pleistocene. The result was the deposition of a number of glacial and inter-glacial deposits. Studies of the surface geology in the Juan de Fuca Strait indicate that the deposits are characteristic of a rapid glacial retreat, followed by a rapid change in sea level (Hewitt and Mosher, 2001). Four main surficial geological units have been identified in recent investigations by Hewitt and Mosher (2001). Unit 1 is bedrock, made up primarily of Cretaceous and Tertiary sedimentary rocks. Unit 2 consists of ice contact sediments such as till or diamicton. Unit 3 is comprised of glacial-marine deposits and Unit 4, composed of two sub-units, is identified as post-glacial sediments.

The majority of Victoria Bight is classified as post-glacial (Unit 4a). These are organic-rich sandy-mud sediments with shell fragments. There are bedrock (Unit 1) outcrops at Albert Head and William Head. Constance Bank is composed mainly of glacial marine till (Unit 2). Just north of Constance Bank there is a field of sand waves, an indication that sediments are actively being transported. The eastern side of Victoria Bight (in the vicinity of Clover Point) is dominated by coarse pebbles and sands of post-glacial Unit 4b. The latter is likely a reworked and winnowed form of 4a. Unit 4b was deposited in a high-energy environment. It is likely that the strong currents in this area have removed the clay and silt fractions of the deposit leaving a pavement-like seafloor (Hewitt and Mosher, 2001) (Figure 5.).

There are no significant river inputs to the Juan de Fuca Strait resulting in a lack of modern sediments. It is more likely that the erosion of thick pre-existing deposits, such as the Dallas Road bluffs, and the erosion and reworking of older deposits provide sediment to Victoria Bight (Hewitt and Mosher, 2001; GeoSea, 1999).

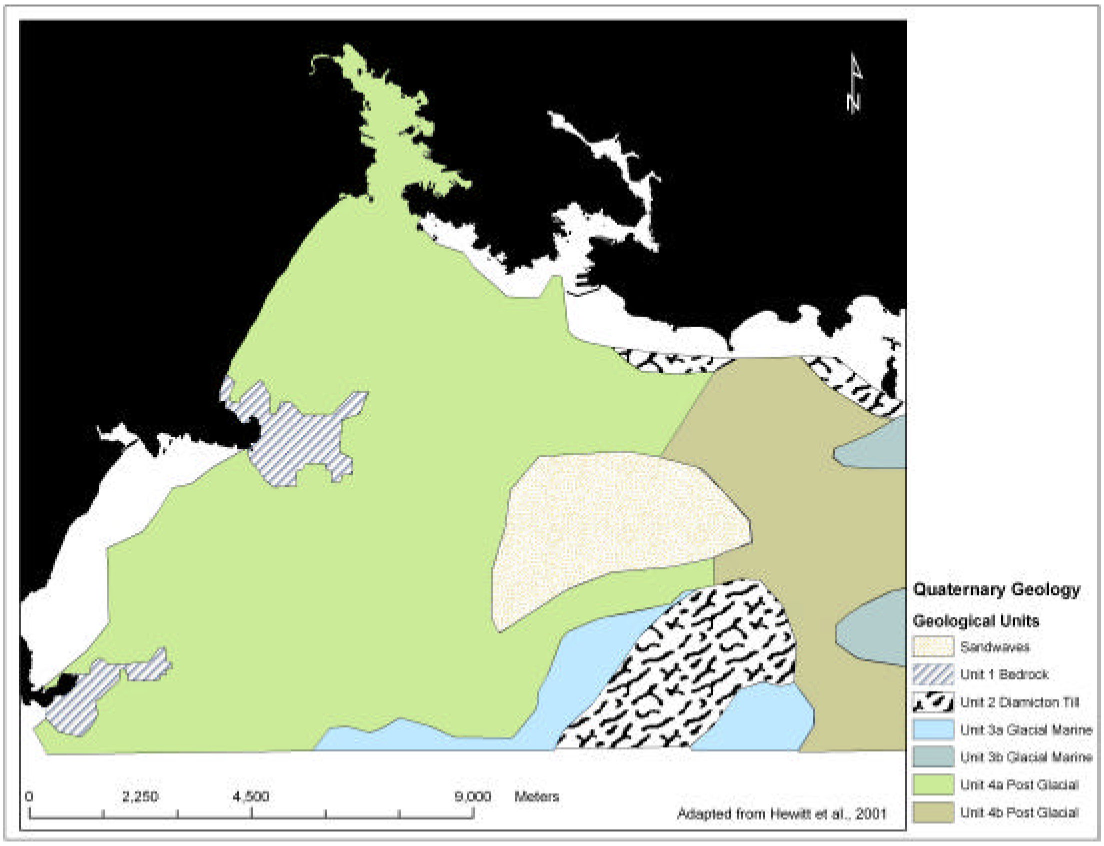


Figure 5. Quaternary Geology of Victoria Bight

3.2 Temperature and Salinity

The waters of the Juan de Fuca Strait remain cold year round. Due to direct exposure to the Pacific Ocean, temperatures beneath depths of 10m remain below 13°C. Also, surface waters are prevented from retaining heat because of the mixing effect created by the strong tidal streams that flow through the eastern passes adjoining the Strait (Thomson, 1981). During the winter months, water temperatures in Victoria Bight are generally between 6°C - 8°C. There is relatively little change in water temperature with a decrease in depth, particularly in the eastern portion of the study area, because of the severe tidal mixing in the eastern passages (Thomson, 1981).

Salinity in the Juan de Fuca Strait generally increases from east to west. Thomson (1981) describes the spatial distribution of salt as a "wedge of saline water that has penetrated up-channel from the Pacific Ocean". The salinity levels in Victoria Bight are normally between 30-31‰. In the spring, there is an influx of fresh water from the

Fraser River into the Strait of Georgia. The fresh water migrates into the Juan de Fuca Strait and salinity levels in Victoria Bight can drop to 28-30‰. As is the case with water temperature, the seasonal variation in salinity is small. Other influences such as oceanic conditions, river runoff and tidal processes have a greater effect on both water temperature and salinity in Victoria Bight (Thompson, 1981).

3.3 Wind Patterns

The prevailing wind patterns in Victoria Bight can be divided into two categories classified by season (Figure 6). During the winter months (October to March), winds are predominantly from the north and northeast (approximately 45% of the time). Average winter wind speeds in Victoria Bight range from 4.5-9.0m s^{-1}. From June to September, prevailing winds are from the southwest (76% of the time). During the summer months wind speeds average 7.5m s^{-1} (Thomson, 1981).

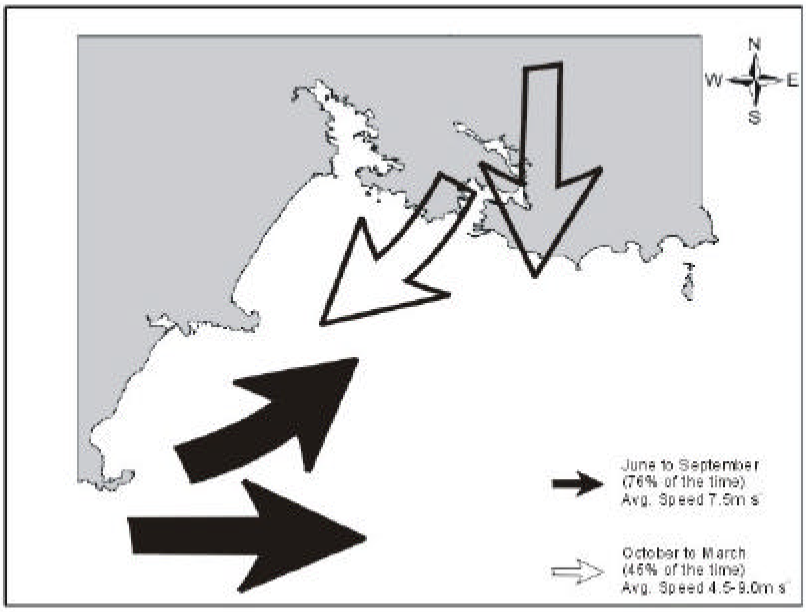


Figure 6. Prevailing Winds in Victoria Bight

3.4 Tides and Currents

The two main tidal components of interest in Victoria Bight are the semidiurnal wave (M_2 tide) and the diurnal wave (K_1 tide). The M_2 tide is associated with the gravitational pull of the moon, and the number '2' indicates the number of cycles in a day. The K1 tide, '1' indicating one cycle per day, is a result of the declination of the sun or moon. The tide in Victoria Bight is classified as mixed, mainly diurnal. In Victoria Bight the K1 tide tends to dominate, and the result is one full tidal cycle per day, with one high water and one low water, 20 days of each month. The mean tidal range in the study area is 1.85m (Thomson, 1981).

The tidal currents in Juan de Fuca Strait are characterized by a weaker flood (incoming tide), and a stronger ebb (outgoing tide). During the flood tide, the majority of water from Juan de Fuca Strait (approximately 50%) goes through Haro Strait. Rosario Strait receives 20%, and 25% goes through Admiralty Inlet into Puget Sound. In general, Victoria Bight is subject to maximum ebbs of 1.80m s^{-1} and floods of 1.50m s^{-1} (Thomson, 1981).

There is a current meter located near each of the CRD outfalls. The instruments are located approximately 10m above the sea floor. Data for each current meter are summarized in Figures 7a and 7b and show that the strongest and most frequent currents near the Macaulay Point outfall are to the southeast; 31% of the time with a mean velocity of 26cm s^{-1} and a maximum velocity of 78cm s^{-1}. The strongest and most frequent currents near the Clover Point outfall are easterly (54% of the time with a mean velocity of 36cm s^{-1} and a maximum velocity of 117cm s^{-1}) (GeoSea, 1999).

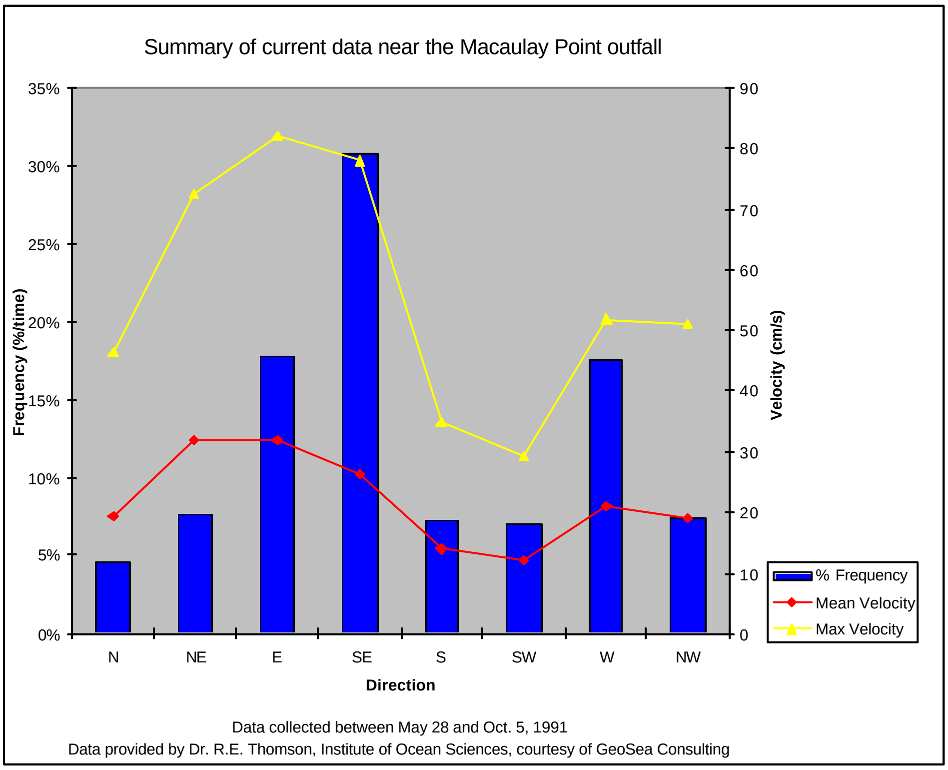


Figure 7a. Macaulay Point current meter data

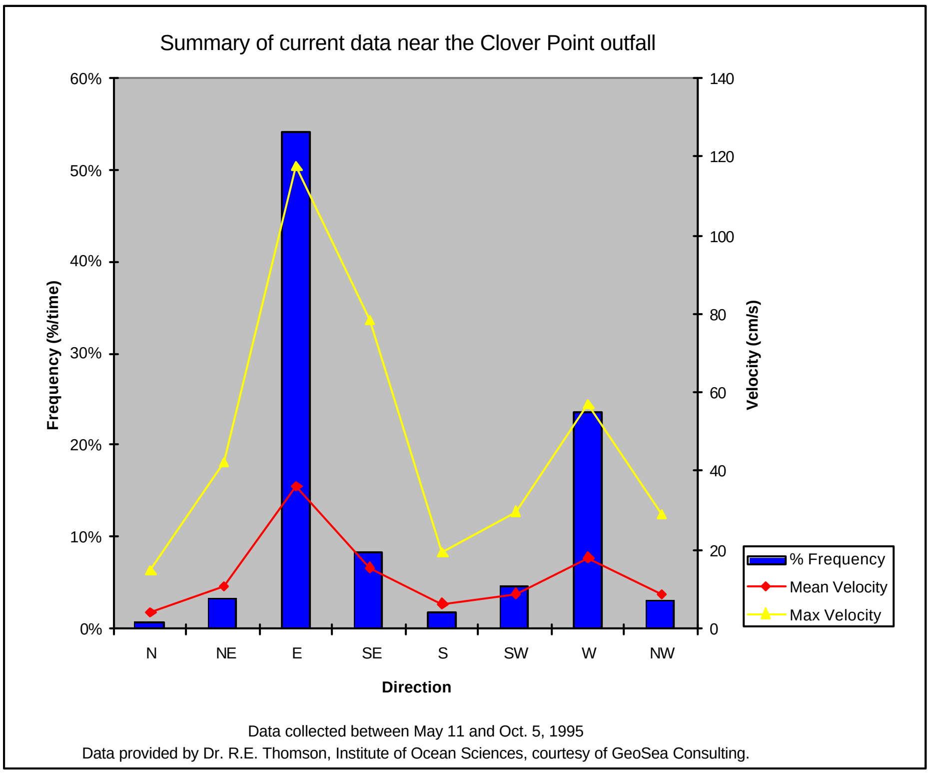


Figure 7b. Clover Point current meter data

4.0 Field Methods

4.1 Sample Design

The research study area is defined by the geographic extent of Victoria Bight. Sediment sample sites were determined using a custom extension in ESRI's *ArcView* GIS software program. Figure 3 shows the proposed sample sites for the project. Sample locations were generated in a hexagonal grid with 500m spacing. A total of 582 sample sites were created. Coordinates for each location were subsequently uploaded into GeoSea Consulting Ltd.'s proprietary software program, *NavPro*. The spatial reference system used for the coordinates is UTM zone 10 (projection), NAD 83 (datum).

4.2 Sample Collection

4.2.1 Sediment Grain-Size Samples

Sediment grab samples were collected between October 18th and November 1st, 2001, using *GeoSea* – a 50 foot steel motor-sailor. Navigation to each sample site was achieved using *NavPro*, a real-time DGPS navigation software program. The program was run through a Toshiba laptop computer linked to a Trimble DGPS unit, providing a typical accuracy of $\pm$5.0m. In most cases samples were collected at the proposed sample stations. However, due to the nature of the sample design software, some sites were located in dangerous or un-navigable waters, such as shoals, or areas too shallow to sample. In such cases samples were either collected as close as possible to the proposed site, or they were eliminated from the sample program.

The *GeoSea* is equipped with a hydraulic hydrographic winch and a stainless steel Shipek grab sampler. The Shipek grab is ideal for sampling surface sediments, collecting the top 5 to 15cm of sediment depending on the firmness of the seabed. Sampling protocol appropriate for heavy metal analysis was used throughout the sampling program. At each sample site the grab was lowered until it made contact with the seabed; at which point the current location of the vessel was recorded. For each successful grab, two representative samples were taken using a stainless steel spatula. Samples were put into Ziploc plastic bags and labelled using an electronic DYMO

Marker labelling system. One sample was put into each of two large plastic pails. Parameters such as sample date, volume, colour, depth, and notes (presence of biota, shell debris, terrestrial detritus etc.) were electronically recorded in the *NavPro* software program. A separate log was kept in a notebook recording weather and sea conditions, and any incidents or anomalies during sampling. In between sample stations, the stainless steel sampling spatula and the 'bucket' portion of the grab (i.e. the section that carries the sediment) were cleaned with sea water, then with Sparkleen detergent followed by a final rinse with distilled water. In cases where the grab only retrieved large cobbles, insufficient sediment, or molluscs, two additional drops of the grab were performed in an attempt to retrieve sediment. Sites were designated as 'Hard Ground' if insufficient sediment was retrieved after three separate drops of the grab. Of the 582 proposed sample sites, 551 sites were actually visited. Of these, 51 sites were designated as 'Hard Ground' (Figure 8).

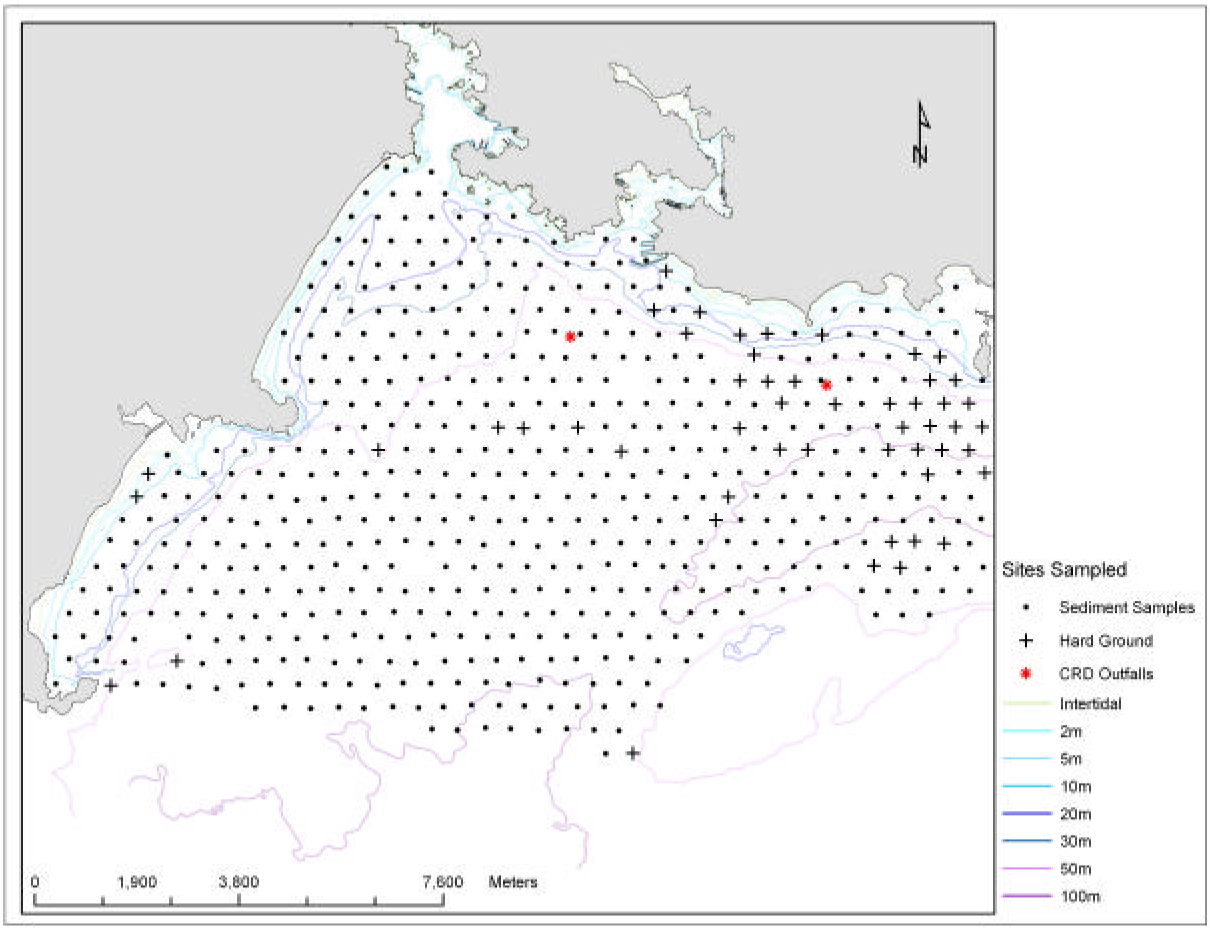


Figure 8. Sample sites visited. Hard Ground samples indicated.

4.2.2 Sample Complications

At the end of the sampling program half of the samples (1 of each duplicate) were brought to the laboratory at GeoSea Consulting Ltd., Brentwood Bay B.C., for grain-size analysis. Prior to that, at the end of each sampling day, the remaining samples were brought to Royal Roads University, Victoria, B.C., where they were stored in a laboratory freezer until heavy metals analysis was to take place in March 2002.
The laboratory freezer used to store the samples was temporarily located in a trailer because of renovations taking place at the university. Due to a break-down in communication, the frozen sediment samples were mistakenly thrown out by Royal Roads University staff. After consultations with University personnel and project sponsors, an arrangement was agreed upon to re-collect a number of samples for heavy metal analysis.

4.2.3 Sediment Heavy Metal Samples

Prior to sample collection, the grain-size data gathered from the original sample set were used to determine what sample stations should be re-visited. Using *ArcView* GIS, samples were selected that were comprised of at least 50% fine sand. Therefore, in order to be selected, 50% of a sample's particle size distribution had to be less than, or equal to 250µm. This criterion was selected because of the association of contaminants with fine particles (Power and Chapman, 1992). Of the 551 sediment samples, 360 sample sites were selected for re-sampling (Figure 4).

Samples were collected between April 3rd and April 11th, 2002, using the *Aluminator* -- a 20 foot aluminium survey vessel, owned and operated by Mr. Doug Hartley. Navigation was achieved using a Garmin DGPS, with ±5.0m accuracy, interfaced with a laptop computer running real-time GPS tracking software and a *Fugawi* electronic charting system. A Ponar grab sampler was used to collect the sediment samples. Depending on the condition of the seabed, the Ponar samples the top 5 to15cm of sediment.

The same sampling protocol used in collecting the initial sediment samples, as described in section 4.2.1, was followed during this sampling program. Of the 360 sites selected for re-sampling, sufficient sediment samples for heavy metal analysis were retrieved at 264 locations (Figure 9). Samples were transported to Portside Marina, Brentwood Bay, at the end of each day. Samples were stored in a refrigerator and kept at a temperature of approximately 4°C, until they were prepared for analysis. Samples were designated 'No Sample' if insufficient amounts of sediment were retrieved after three separate drops of the grab. One notable exception to this is the small group of missed samples in the southwest quadrant of the study area. These sites were abandoned due to heavy seas and dangerous conditions.

The rather large number of 'No Sample' sites stems from the fact that the proposed sample sites were based on the grain-size sample data. A much smaller sample size is required for grain-size analysis than for heavy metal analysis, and what was a sufficient amount of sample for grain-size analysis, was not necessarily enough for metal analysis. For this reason, a large number of sites where grain-size data was acquired failed to yield enough sediment for metal analysis.

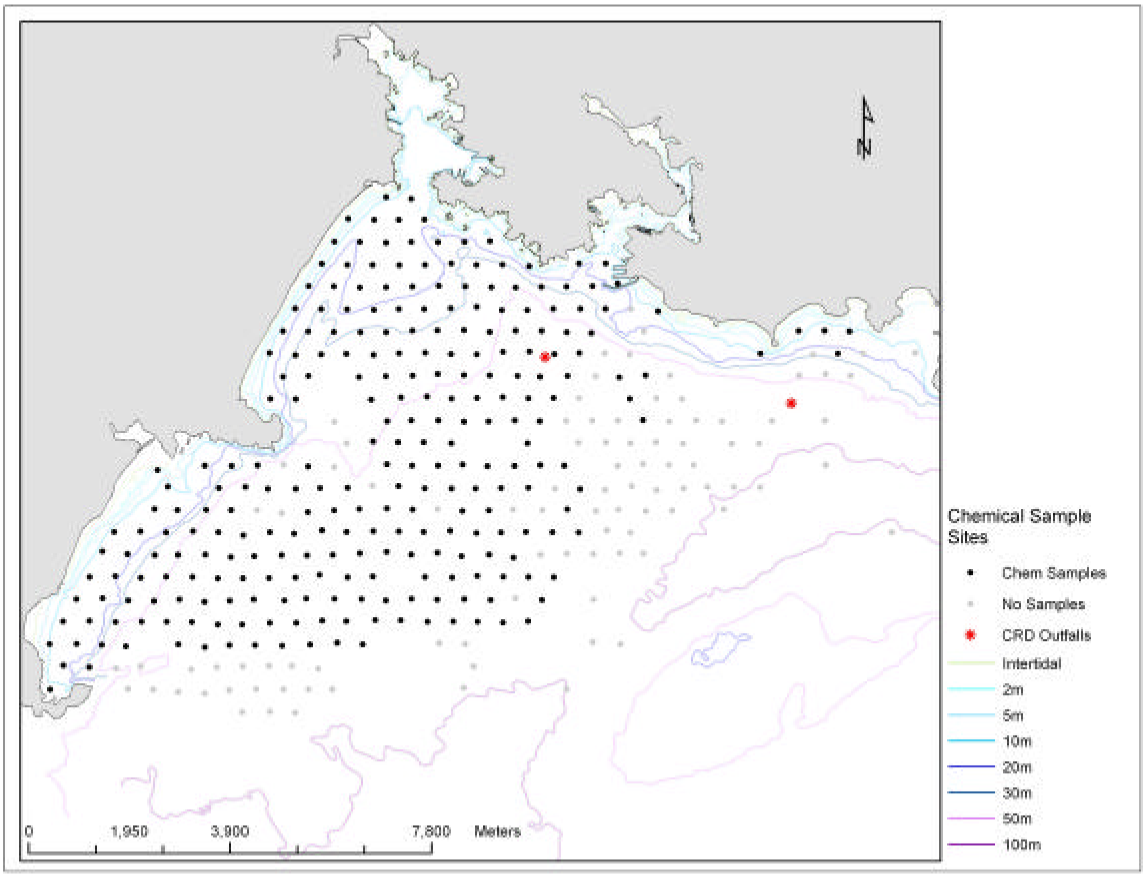


Figure 9. Samples collected for heavy metal analysis. 'No Sample' sites indicated.

5.0 Laboratory Methods

The sediment samples collected for this study were subject to two forms of analyses. Grain-size analysis was conducted to generate a high resolution survey of the sediment types in the receiving environment, and to determine potential areas of contaminant build-up based on the association between contaminants and fine particles (Zhang et al., 2001; Power and Chapman, 1992; McLaren and Little, 1987). Upon completion of grain-size analysis, a second set of samples were collected (see section 4.2.2), and analyzed for heavy metals, specifically Chromium, Copper, Nickel and Zinc. To validate any relationships or comparisons between sediment grain-size and contamination, the two sediment sample data sets were compared. Eight samples, distributed throughout the study area, were chosen to determine the percent similarity of the grain-size distribution between the two sediment sample data sets. Percent similarity is defined as 100 times the ratio of the area of the intersection of the two distributions to the area of the union of the two distributions. On average, samples were 90.6% similar (Table 1).

Table 1. Sediment Data Percent Similarity

Sample ID	Percent Similarity
140 140Chem	87.6%
179 179Chem	90.0%
203 203Chem	95.0%
307 307Chem	94.9%
425 425Chem	94.5%
525 525Chem	95.6%
549 549Chem	77.5%
74 74Chem	89.8%
Average % Similar	**90.6%**

5.1 Sediment Grain-Size Analysis

Sediment grain-size analysis was carried out using the sediment laboratory facilities at GeoSea Consulting Ltd., between November 6th and November 28th, 2001. The methodology used for grain-size analysis was developed by GeoSea Consulting Ltd. The complete grain-size distribution, from 0.02 µm – 4.0mm (1mm = 1000µm) was determined for each sample (Table A-1, Appendix 1). Grain-size distributions were used to classify samples based on the grain-size scales in Table 2.

5.1.1 Malvern Mastersizer 2000 Laser Particle Sizer

A Malvern Mastersizer 2000 laser particle size analyzer was used to measure grain-size between 0.02 - 1000µm. The instrument is based on the principle of laser diffraction. Light from a low power helium-neon laser is used to form a collimated, monochromatic (red) beam of light which is the analyzer beam. The unit also has a solid state blue light source. The shorter wavelength of the blue light allows for greater accuracy in the sub-micron range. Particles from sediment samples enter the beam via a dispersion tank that pumps the material, carried in water, through a sample cell. The resultant light scatter is incident onto the detector lens. The detector lens acts as a Fourier Transform Lens forming the far field diffraction patterns of the scattered light at its focal plane. Here a custom designed detector in the form of 52 concentric rings gathers the scattered light over a range of solid angles of scatter. When a particle is in the analyzer beam its diffraction pattern is stationary and centered on the optical axis of the range lens. Un-scattered light is also focused onto an aperture on the detector. The total laser power exiting the optical system through this aperture enables measurement of the sample concentration (GeoSea, 2000).

In practice, many particles are simultaneously present in the analyzer beam and the scattered light measured on the detector is the sum of all individual patterns overlaid on the central axis. During analysis, the instrument was set to take 30,000 such measurements (snaps), which are then averaged to build up a light scattering characteristic for that sample based upon the population of individual particles. Applying the Mie theory of light scattering, the output from the detector is then processed by a computer, generating a final distribution.

Particles scatter light at angles related to their diameter (*i.e.*, the larger the particle, the smaller the angle of scatter and *vice versa*). Over the size range of interest, which is 0.02µm and larger for this instrument, scattering is independent of the optical properties of the medium of suspension or the particles themselves. Through a process of constrained least squares fitting of theoretical scattering predictions to the observed data, the computer calculates a volume size distribution that would give rise to the observed scattering characteristics. No *a priori* information about the form of the size distribution is assumed, allowing for the characterization of multi-modal distributions with high resolution (GeoSea, 2000).

5.1.2 Grain-Size Analysis Technique – Laser Analysis

GeoSea Consulting Ltd. had developed a standard operating procedure (SOP), which was used for this project, for the Malvern Mastersizer 2000 laser particle size analyzer. This ensured that all parameters and variables remained consistent throughout sample analysis. The methodology covers the range of sizes normally considered important in sediments, is relatively rapid and requires only small samples. No chemical pre-treatment of the samples was undertaken prior to analysis.

Prior to every analysis, the Mastersizer 2000 automatically aligns the laser beam, and a background measurement of the suspension medium is taken. Samples were initially well mixed before obtaining a representative sub-sample for analysis. The amount of sediment required is about 2 to 4g for sands and 0.5 to 1g for silt and clay. Samples are introduced into the dispersion unit by wet sieving through a 1mm mesh, eliminating possible blockage of the pumping mechanism by particles that are too large. Disaggregation of the sample is achieved by both mechanical stirring and mild ultrasonic dispersion in the sample dispersion unit. If material remains on the 1mm sieve, a sub-sample is oven dried in preparation for dry sieving (GeoSea, 2000).

Table 2. Grain-Size Scales for Sediments

U.S. Standard Sieve Mesh Number	Diameter (*mm*)	Diameter (*µm*)	Phi Value (?)	Wentworth Size Class	Sediment Type
5	4.00		-2.00		
6	3.36		-1.75		
7	2.83		-1.50	Granule	GRAVEL
8	2.38		-1.25		
10	2.00		-1.00		
12	1.68		-0.75		
14	1.41		-0.50	Very Coarse	
16	1.19		-0.25	Sand	
18	1.00		0.00		
20	0.84	840	0.25		
25	0.71	710	0.50	Coarse	
30	0.59	590	0.75	Sand	
35	0.50	500	1.00		
40	0.42	420	1.25		
45	0.35	350	1.50	Medium	SAND
50	0.30	300	1.75	Sand	
60	0.25	250	2.00		
70	0.21	210	2.25		
80	0.177	177	2.50	Fine	
100	0.149	149	2.75	Sand	
120	0.125	125	3.00		
140	0.105	105	3.25		
170	0.088	88	3.50	Very Fine	
200	0.074	74	3.75	Sand	
230	0.0625	62.5	4.00		
270	0.053	53	4.25		
325	0.044	44	4.50	Coarse	
	0.037	37	4.75	Silt	
	0.031	31	5.00		
	0.0156	15.6	6.00	Medium Silt	
	0.0078	7.8	7.00	Fine Silt	
	0.0039	3.9	8.00	Very Fine Silt	MUD
	0.002	2	9.00		
	0.00098	0.98	10.00		
	0.00049	0.49	11.00	Clay	
	0.00024	0.24	12.00		
	0.00012	0.12	13.00		
	0.00006	0.06	14.00		

5.1.3 Grain-Size Analysis Technique – Sieve Analysis

In cases where sample grain-size distributions required sieving in addition to laser analysis, the weight percent for each of the coarse sizes (4.0mm to 0.7mm) was obtained by sieving at 500µm intervals. A sub-sample was dried overnight, at 80°C. Dried sub-samples were placed into a stack of sieves, and shaken for a period of 2 minutes using a Gilson Sieve Shaker. Using a laptop computer, interfaced with a Denver Instruments balance, and running software developed by GeoSea (*SieveWeight*), weights for each coarse fraction were registered and recorded in a computer file.

5.1.4 Grain-Size Data Merging Technique

A Software program (*MalvMerge*) developed by GeoSea Consulting Ltd. was used to merge the dry-sieved weights and measurements from the Malvern laser instrument into a final distribution within the range of 0.02µm – 4.0mm, in size bins of equal width (500µm). The results from the Mastersizer 2000 consist of a set of 52 size bins, where the bin width is inversely proportional to the mean particle size in the bin, with the percentage of material in each bin. A summary of the merging process follows: Sieving is carried out at 500µm intervals from 4.0mm to 0.7mm. The weights are normalized and the percentage smaller than 0.7mm is used to renormalize the Malvern values using the methods described above. The portion of the lens data above 0.7mm is removed and replaced with sieve data (GeoSea, 2000).

Data produced by the *MalvMerge* program are interpreted as follows: the weight percentage shown under a size heading is the amount of material found in a bin with size boundaries set by the previous size heading as the upper size limit and the current size heading as the lower limit. For example, the weight percent shown under the heading 350µm is the amount in the bin bounded by 500µm and 350µm. Because of the way the file is written the first size fraction in the list (4.0mm) always has zero weight percent (Table A-1, Appendix 1).

5.2 Heavy Metals Analysis

Samples were prepared for heavy metals analysis using the laboratory facilities at GeoSea Consulting Ltd., between April 26th and May 7th, 2002. Sample analysis was carried out using the laboratory facilities at Royal Roads University, on two separate occasions; from May 15th to May 29th, 2002 and from August 27th to September 5th, 2002.

5.2.1 Sample Preparation

Prior to metals analysis, samples were prepared for acid digestion via a number of steps. Throughout the preparation process, care was taken to ensure that no contamination or cross-contamination of samples occurred.

Samples were initially well-mixed to ensure homogenization. Subsequently, a sub-sample was taken (approximately 30 – 60g wet weight), using a stainless steel spatula, and placed into a plastic beaker. The beakers were weighed and put into a drying oven, where the samples were dried overnight at a temperature of 70°C. The samples were then removed from the oven and weighed using a Denver Instruments digital balance. After weighing, the samples were put back into the oven and left for approximately 1 hour. The samples were then removed and weighed a second time. Using the two dried weights, the constant weight, as a percentage, was calculated using the following formula: $100 \times ((M2 - M1)/M1)$, where $M1$ is the initial mass of the sample after initial drying, and $M2$ is the final mass of the sample after another hour of drying. All samples were less than 3% different, indicating no significant weight change between the initial and second drying. The percent moisture for each sample was calculated using a similar formula: $100 \times ((WW - DW)/WW)$. In this case, WW is the initial wet weight of the sample, and DW is the final dried weight of the sample. Table A-2 (Appendix 2) shows the results for the constant weight and percent moisture calculations for each sample.

Having calculated the constant weight and percent moisture, each dried sample was re-homogenized using a pestle and mortar to break apart any material that had aggregated during the drying process. Samples were then passed through a stainless steel 250µm sieve to remove any large particles. Approximately 20g of each prepared sample was stored in a plastic Ziploc bag for metals analysis.

5.2.2 Sample Digestion

Sample digestion was carried out based on the U.S. EPA's solid waste test method 3050B – *Acid Digestion of Sediments, Sludges and Soils*. This technique was selected because it is a well-established method of extracting heavy metals for subsequent Flame Atomic Absorption (FAA) spectrometry analysis. This is a strong acid digestion designed to dissolve elements, including Cr, Cu and Zn, that could become environmentally available (U.S. EPA, 1986). Samples were processed in batches of 12. All sample digestions were conducted under a fume hood.

The digestate was stored in glass vials, and kept refrigerated until FAA analysis. Throughout the entire digestion process, steps were taken to minimize the risk of contamination or cross-contamination of samples. A number of method blanks were run to monitor any potential contamination during the digestion procedure. The method blanks were subject to the entire digestion process, and differed only from other samples in that they contained no sediment. All glassware used throughout the sample digestion was acid washed, using a process whereby each piece of glassware was rinsed with 1:1 HNO_3; 1:1 HCl followed by distilled water until the rinsate was neutral.

5.2.3 Flame Atomic Absorption Spectrometry

The digestates were analyzed by flame atomic absorption spectrometry (FAA) using a Varian AA1475. Prior to FAA analysis, a number of calibration standards for Cr, Cu, Ni and Zn were created. Standard solutions for each metal were diluted with reagent water to create solutions with the following concentrations: 5.0µg/mL; 2.5µg/mL; 1.0µg/mL; 0.5µg/mL; and 0.25µg/mL. Calibration standards were run through the instrument at the beginning of each analyses session, and after every batch of 50 samples analyzed. Sample batches were subsequently reduced to 25 samples, increasing the frequency of calibration standard analysis.

Sample analysis was conducted for one metal at a time. Digestate (or calibration standard) was introduced into the FAA and aspirated. The instrument indicated a light absorbance value, which when stabilized – after a few seconds, was manually recorded onto a spreadsheet (Table A-3, Appendix 2).

6.0 Results and Discussion

6.1 Sediments in Victoria Bight

6.1.1 Sediment Type

Sediment grain-size analysis indicates that the majority of sediments in the study area are dominated by sand and muddy sand, which combine to make up 87.1% of the sediments in the Victoria Bight. A summary of the sediment types identified in Victoria Bight is shown in Table 3.

Table 3. Summary of Sediment Types

Sediment Type	Count	% of Samples
Hard Ground (HG)	51	9.3%
Gravely Sand (GS)	9	1.6%
Sand (S)	244	44.3%
Muddy Sand (MS)	236	42.8%
Sandy Mud (SM)	6	1.1%
Mud (M)	5	0.9%
Total	**551**	**100.0%**

The grain-size distributions for each sample (Table A-1, Appendix 1) were entered into ESRI's ArcMap GIS software program. Using the Spatial Analyst module, a sediment type surface was generated using a tension-spline algorithm. The resultant sediment type surface is plotted in Figure 10. The study area seems to be divided into 3 general types of bottom that correspond with the quaternary geology presented in Section 3.1. The area in the vicinity of Clover Point and the Trial Islands, down to the northeast section of Constance Bank is dominated by an area of hard ground and coarse sediments. The southern portion of the study area is comprised mainly of coarse sediments. Based on the association between grain-size and contaminants, little contamination would be expected in these areas. The northern section, near Royal Roads and the Macaulay point outfall, along with the southwestern portion of the study area in the vicinity of Parry Bay, is characterised by finer sediments (generally muddy sand; Figure 10). Based on the grain-size data, contaminated sediments are more likely to be found in these areas.

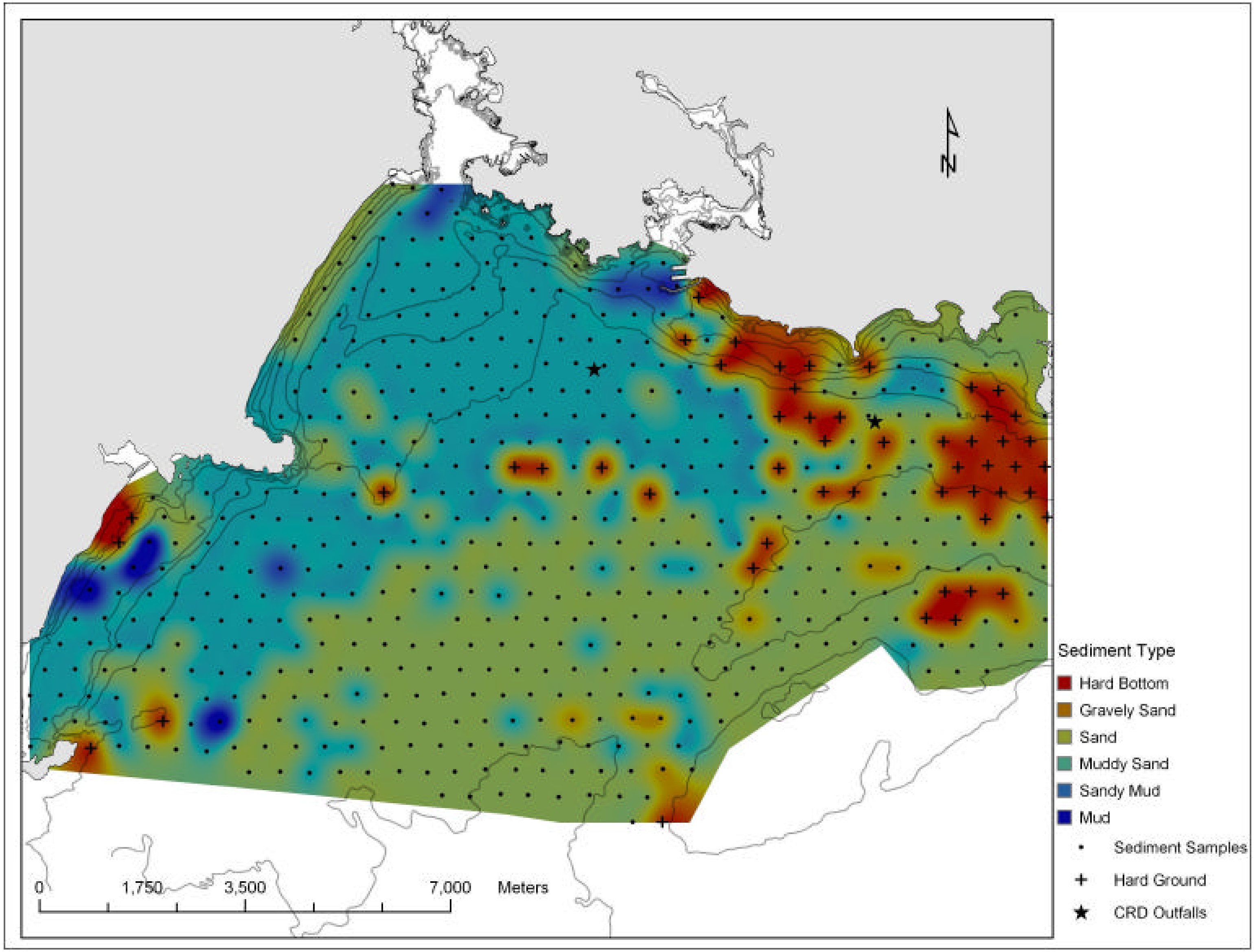


Figure 10. Sediment Types

6.1.2 Fine Sediments

The association between metals and fine sediments, particularly the fraction less than 62µm, is well documented (Zhang et al., 2001; Padmalal et al., 1996; Power and Chapman, 1992; McLaren and Little, 1987; Young et al., 1985). In an effort to gain a better understanding of the receiving environment, in terms of identifying areas of potential contamination, the sediment data were mapped based on the percentage of fines (<62µm) in each of the sediment samples (Figure 11). There are two areas within Victoria Bight where sediment distributions have a high percentage of fine particles. The northern portion of the study area, west of the entrance to Victoria Harbour, and the southwestern section between Albert Head and William Head have the highest percentage of fine particles. Along with other smaller pockets of fine sediments, the areas described above likely have the greatest potential for elevated metal levels.

6.2 Derivation of Contaminant Values

6.2.1 Interpretation of FAA Light Absorbance Values

Contaminant values for the metals of interest were determined using the light absorbance values from the FAA instrument (Table A-3, Appendix 2). Light absorbance values for calibration standards were plotted in an XY scatter plot and a line of best fit was generated. The values from the equation of the line, $y = mx + b$, were incorporated into the following expression:

$$x = \left[\frac{\left\{ \frac{(y-b)}{m} \right\} \times v}{g} \right]$$

where x is the analyte concentration in µg g^{-1}

y is the FAA light absorbance value

b is the y-intercept

m is the slope of the line

v is the volume to which the digestate was diluted to in mL

g is the amount of sediment analyzed in g

Resultant contaminant values (dry weight) are found in Table A-4, Appendix 2.

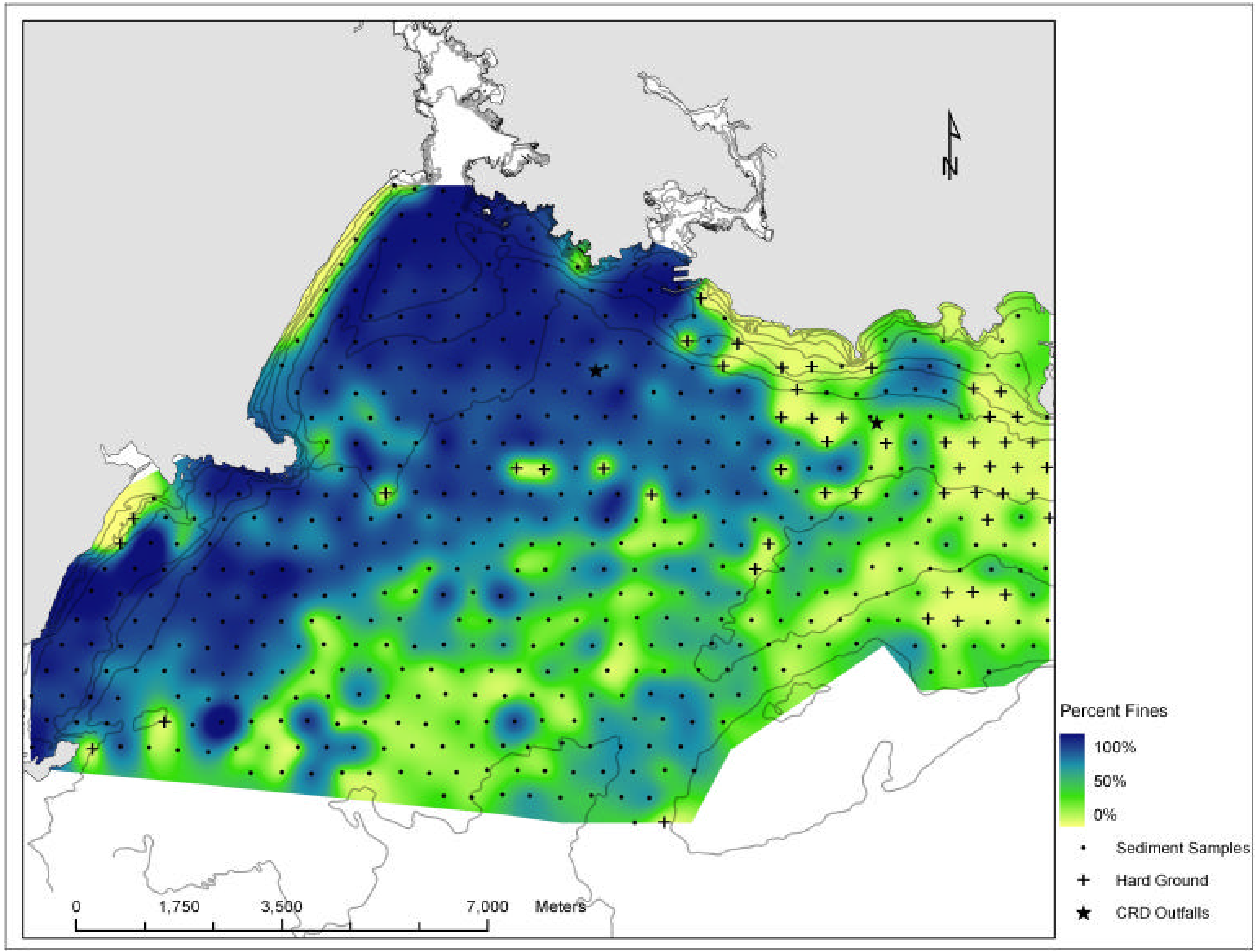


Figure 11. Percent Fines (<62µm)

6.2.2 Quality Assurance and Quality Control (QA/QC)

QA/QC was carried out using method blanks and duplicate samples. The method blanks were used to determine if any contaminants were being introduced during the digestion procedure. The results of the method blank analysis are found in Table 4.

Table 4. Method Blank Values

	Cr µg L^{-1}	Cu µg L^{-1}	Ni µg L^{-1}	Zn µg L^{-1}
BLANK 1	38.58	BDL	2.27	30.68
BLANK 2	27.52	26.3	18.82	36.88
BLANK 3	38.64	22.5	BDL	24.88
BLANK 4	BDL	22.5	BDL	BDL
BLANK 5	BDL	23.0	29.70	23.33
BLANK 6	BDL	17.4	BDL	25.55
Blank Avg	**17.46**	**18.63**	**8.47**	**23.55**

The values for the series of blanks were averaged, and the averaged values were subtracted from each sample to obtain a corrected metal concentration (Table A-5, Appendix 2). Samples below detection limit (BDL) were assigned a value of one half of the detection limit (Pascoe, T. Pers. Comm., 2003). The detection limit for the FAA instrument is taken as 1.0µg/g; therefore all BDL values were calculated as 0.50µg/g.

Duplicate samples were used to monitor the performance of the FAA instrument. For each duplicate, the relative percent difference (RPD) was calculated:

$$RPD = 100\left[\frac{(x1 - x2)}{\left\{\frac{(x1 + x2}{2}\right\}}\right]$$

where $x1$ and $x2$ are the concentrations of the analytes. The RPD values for the duplicate samples are listed in Table 5. RPD values were evaluated based on the following guidelines: An RPD between 0-30 is considered good; 30-50 is fair; and 50+ is poor (Dodd, M. Pers. Comm., 2003). The average RPD value for Cr, Cu and Zn is fair, indicating reliable results. Nickel had very poor RPD values and so the Ni data were not used in the evaluation of metal contamination of the sediments in Victoria Bight.

Table 5. Duplicate Samples: Measure of Relative Percent Difference (RPD)

ID	Cr µg g^{-1}	Cr µg g^{-1} dup	Cr µg g^{-1} RPD	Cu µg g^{-1}	Cu µg g^{-1} dup	Cu µg g^{-1} RPD	Ni µg g^{-1}	Ni µg g^{-1} dup	Ni µg g^{-1} RPD	Zn µg g^{-1}	Zn µg g^{-1} dup	Zn µg g^{-1} RPD
80	44.86	44.86	0.00	0.50	0.50	0.00	2.90	16.53	140.34	80.74	86.88	7.32
107	35.96	32.99	8.61	0.50	0.50	0.00	2.90	11.99	122.13	65.41	28.60	78.32
137	0.50	0.50	0.00	8.06	10.38	25.18	0.50	0.50	0.00	11.27	8.33	29.98
203	0.50	0.50	0.00	9.02	9.02	0.00	14.64	27.84	62.16	12.56	11.17	11.71
205	0.50	0.50	0.00	0.50	0.50	0.00	14.35	1.16	170.10	7.31	8.49	14.95
234	10.07	10.07	0.00	19.13	19.13	0.00	21.10	15.73	29.19	24.39	28.41	15.24
238	25.73	12.09	72.12	11.37	6.37	56.35	0.50	3.21	146.06	14.48	41.36	96.27
266	1.75	55.94	187.87	3.11	12.27	119.04	31.86	58.74	59.34	21.37	228.54	165.80
268	0.50	0.50	0.00	6.72	6.72	0.00	27.84	11.34	84.25	58.67	102.00	53.94
275	1.51	32.28	182.09	0.50	0.50	0.00	21.24	1.33	176.45	8.12	8.67	6.62
301	21.93	30.68	33.27	52.41	57.88	9.91	0.50	0.50	0.00	23.97	31.06	25.78
341	44.86	53.76	18.05	36.32	25.33	35.65	25.63	25.63	0.00	37.44	152.63	121.20
368	40.92	46.00	11.68	3.35	91.26	185.83	20.69	6.11	108.78	16.55	24.47	38.59
425	21.93	24.12	9.50	36.32	69.29	62.44	1.07	11.65	166.37	40.06	32.21	21.73
453	10.99	32.87	99.77	68.81	57.88	17.25	1.72	51.88	187.20	40.51	40.51	0.00
474	1.30	19.49	175.05	47.31	25.09	61.38	0.50	0.50	0.00	50.53	26.33	62.97
477	13.23	13.23	0.00	30.55	36.02	16.42	28.33	28.33	0.00	33.42	33.42	0.00
500	50.92	29.55	53.10	8.06	5.74	33.65	0.65	4.36	148.25	26.26	13.92	61.44
506	14.56	13.18	9.99	58.30	25.33	78.84	0.78	5.90	153.47	97.65	19.12	134.51
535	31.28	42.11	29.51	34.22	34.22	0.00	58.63	6.69	159.06	57.74	144.07	85.55
547	56.15	71.38	23.88	52.41	52.41	0.00	20.69	11.94	53.61	45.24	40.51	11.03
554	11.00	59.78	137.84	17.96	9.83	58.52	58.84	24.23	83.34	0.50	0.50	0.00
Average RPD			**47.8**			**34.57**			**93.19**			**47.41**

6.2.3 Potential Sources of Error

In addition to the possible sources of error inherent in any field sampling program, and the potential for sample contamination during laboratory analysis, the following possible sources of error were identified during sample processing and analysis. During the digestion procedure, the H_2O_2 used for the final 17 samples had surpassed the indicated expiration date. The amount of effervescence generated from this H_2O_2 was notably less than in previous instances. The samples affected were: 245, 205, 205D, 241, 207, 247, 278, 173, 104, 237, 168, 213, 50, 300, 180, 145, 582.

Problems with the FAA Ni lamp were noted during analysis. The lamp did not seat properly into the lamp carriage. The light intensity from the Ni lamp was not satisfactory when instrument parameters were set for Ni analysis. Alteration of parameter settings resulted in acceptable light intensity. Light absorbance values for Ni were highly erratic and the instrument had a great deal of difficulty obtaining a stable reading. As noted in section 6.2.2 Ni data were not used to evaluate metal contamination in the study area.

6.3 Spatial and Statistical Analysis

6.3.1 Spatial Distribution of Metals

Spatial analysis of the contaminant data was performed using *ArcMap* GIS software. Surfaces for each of the metals tested were generated using a spline – tension algorithm. Algorithm parameters were set to ensure that individual data points retained their actual value. The maps created provide a visual representation of the distribution and relative level of sediment contamination for Cr, Cu and Zn in Victoria Bight.

Chromium

The distribution of Cr in Victoria Bight is shown in Figure 12. Chromium distribution appears to be somewhat erratic; however, at a broad scale Cr levels tend to be higher in the northern section of the study area down to a latitude just south of Albert Head. The higher levels of Cr in the northern section of the study area appear to coincide well with the distribution of fine particles. In contrast, there are a number of areas where the relationship between particle size and Cr levels is less distinct.

There are two groups of samples along the southern boundary of the study area where Cr levels are elevated, and sediments have a relatively low percentage of fine particles, particularly the group at the southeastern portion of the study area. A possible explanation is the relationship between Cr and heavy mineral content in the sand fraction. Certain heavy minerals are capable of adsorbing Cr (Padmalal et al., 1997). It is possible that the sands in Victoria Bight are rich in these particular heavy minerals.

Another notable observation is the relatively low level of Cr in Parry Bay where the sediments are dominated by fine particles, yet there does not seem to be a positive relationship with Cr. Possibly the rates of deposition for fine sediment is very slow, and consequently, the majority of the sediment in Parry Bay was deposited prior to industrialization in the area, and has remained relatively undisturbed. William Head and Albert Head may be acting as protective barriers, sheltering the sediments in Parry Bay from currents and tides. William Head may be deflecting the incoming tide, and Albert Head may shelter Parry Bay during the ebb flow. During the slightly stronger ebb, Albert Head may cause a gyre to form, resulting in the deposition of sediments on the south side of the point. This may account for the relatively high levels of Cr found here.

Copper

Copper levels in the study area are mapped in Figure 13. Copper concentrations are highest in the northern portion of the study area, and this corresponds well with the distribution of fine sediments in this area. Similar to Cr, there are relatively low Cu levels in Parry Bay, with isolated high values immediately south of Albert Head. Again, this is possibly the result of shelter from currents and tides provided by the headlands on the west side of the study area, as described above. Also analogous to Cr levels, there is a small group of samples at the south end of the study area, adjacent to William Head, with elevated Cu levels.

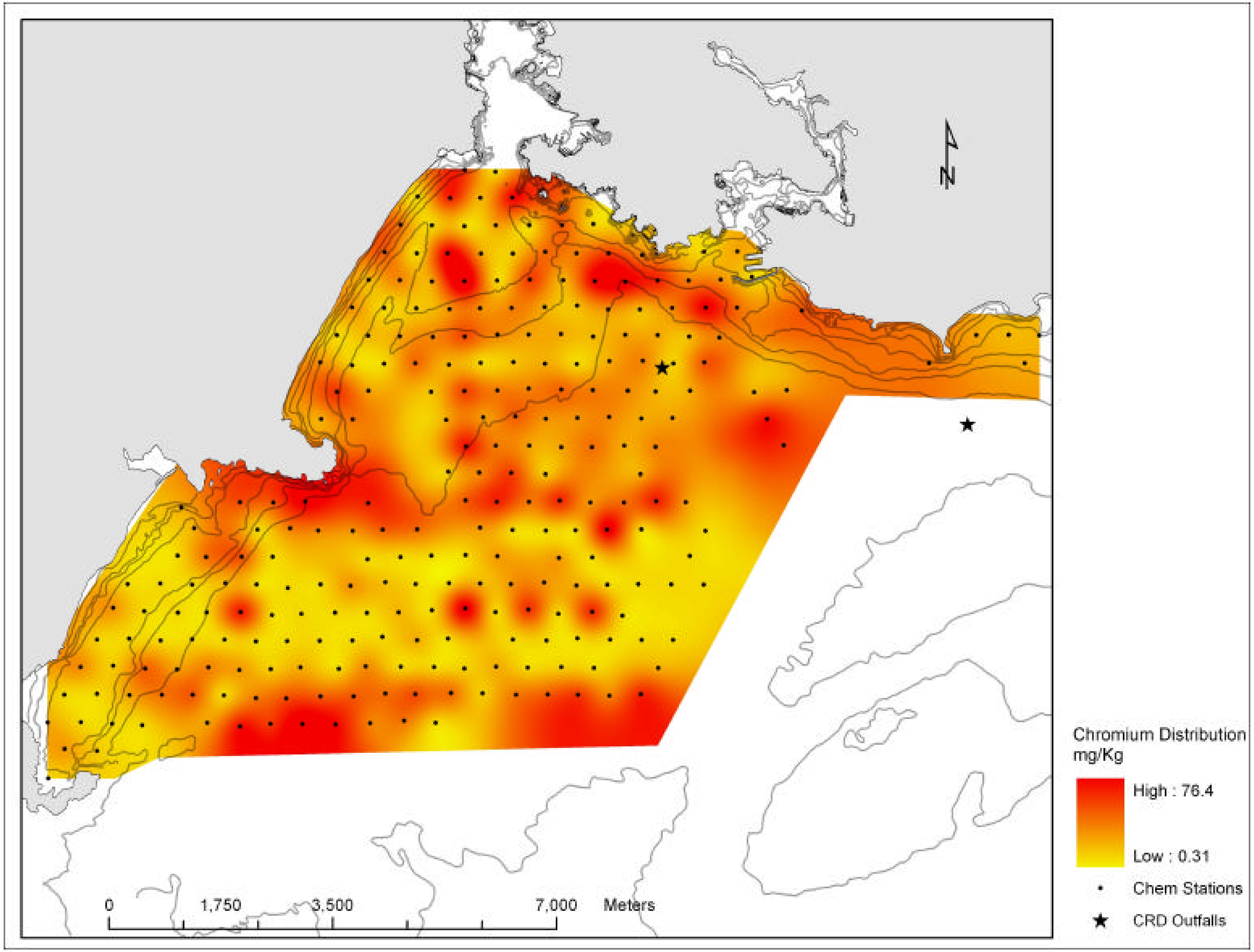


Figure 12. Chromium Distribution

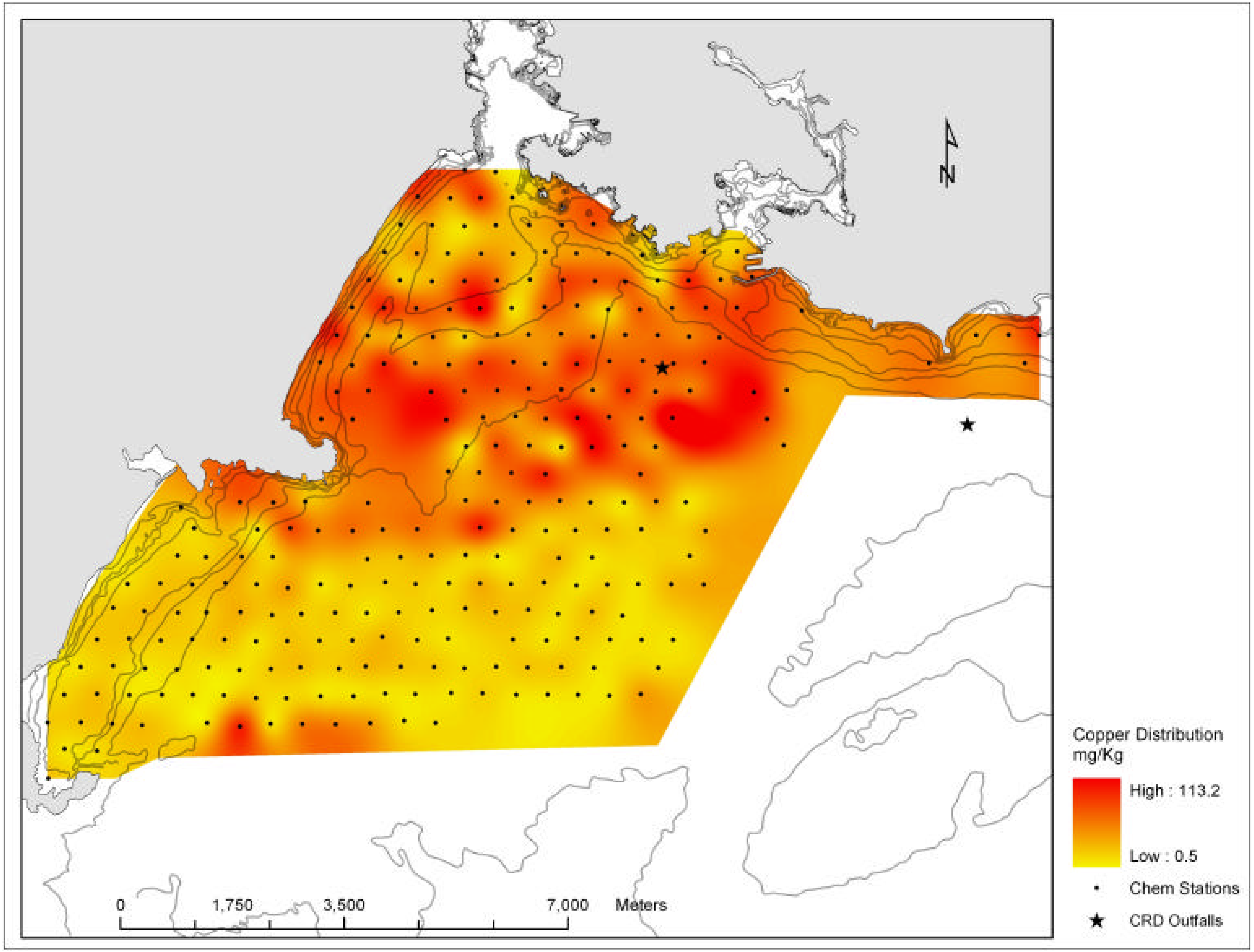


Figure 13. Copper Distribution

Zinc

While less pronounced than Cu, Zn levels in the northern portion of Victoria Bight are generally higher than levels in the southern part of the study area (Figure 14). Again, this corresponds well with fine particles. As was noted with both Cr and Cu, there are relatively high Zn concentrations immediately south of Albert Head, and low Zn levels in Parry Bay. Once more, this pattern may be explained by the hypothesis presented regarding the Cr and Cu observations in this region. Unlike Cr and Cu, there is one sample in Parry Bay, just north of William Head with a high Zn value. It is likely that this sample is an anomaly, since the surrounding four samples all have similar low values. A further similarity between Zn and the other metals are the elevated levels in the group of samples at the south end of the study area adjacent to William Head. Being at the edge of the study area, it is difficult to determine the cause for the elevated metal levels in these samples, however, it seems to be a consistent zone of contaminant build-up.

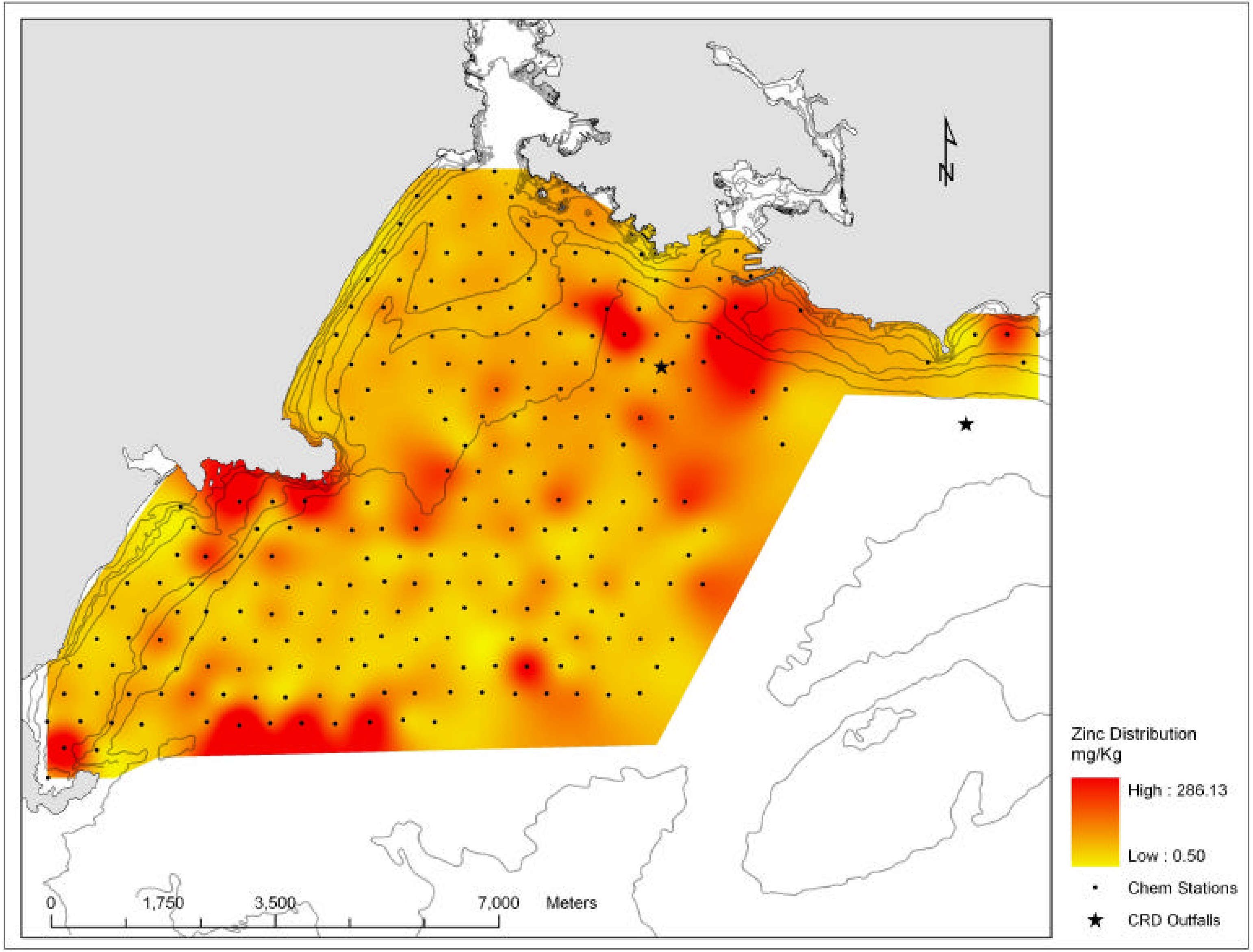


Figure 14. Zinc Distribution

6.3.2 Statistical Analysis

Statistical analysis was used to explore potential relationships between observed metal values, and a number of other variables of interest. Statistics were also used to supplement the insights gained from spatial analysis of sediment metal contamination in Victoria Bight. While it is understood that statistics are not necessarily indicative of cause and effect, nor does statistical significance necessarily translate into practical significance, statistics are still useful in providing weight-of-evidence for hypotheses testing (Sutherland, 2000; Luoma, 1990). All statistical analysis was performed using the software package *SPSS v. 10.0 for Windows*. Data used for statistical analysis are found in Table A-6, Appendix 2.

Raw metal values were used in descriptive and bivariate analysis. Multivariate analysis was also performed, however prior to analysis the contaminant data were transformed to generate two new data sets. The first data set was created using a log10+1 transformation. The log transformation serves to standardize the analyte values and minimize the effects of differences in magnitude in data variability. The addition of the constant 1 was used to avoid negative values (Emmerson et al., 1997; Brakstad, 1992). The log data were further transformed by normalization to percent fines. This transformation was employed to reduce the effects caused by variable grain-size (Birch et al., 2001).

Descriptive Statistics

Basic descriptive statistics for Victoria Bight sediment samples are shown in Table 6. In descriptive statistics the skewness value is a measure of data normality. In general, a skewness value greater than 1.0 is an indication that data are significantly different from a normal distribution. The skewness values in Table 6 indicate that Cr and Zn are not normally distributed. Therefore, further analysis of the data was conducted using non-parametric tests, which do not assume normally distributed data, or the log transformed normalized data.

Table 6. Descriptive Statistics for Untransformed Data

	N	Range	Minimum	Maximum	Mean	Std. Dev.	Variance	Skew	Std. Error
% Fines	264	100	0.0	100.0	39.6	19.79	391.58	-0.22	0.15
% Moist	264	28.3	15.1	43.5	29.4	4.48	20.10	-0.24	0.15
Chromium	264	76.1	0.3	76.5	18.1	18.05	325.92	1.02	0.15
Copper	264	113	0.5	113.0	24.6	22.18	492.05	0.96	0.15
Zinc	264	285.6	0.5	286.1	37.5	44.06	1940.84	2.82	0.15
Valid N	264								

Bivariate Analysis

Using Spearman's Rank coefficient, the correlation between metal concentrations and a number of variables of interest were examined. The first relationship explored was that between metals and percent fines (Table 7). Copper and Zn are both significantly and positively correlated to percent fines. That is, there is a linear relationship between Cu and Zn levels and the percentage of fines in a sample. As the percentage of fine particles increase, it is reasonable to assume that Cu and Zn levels could also potentially increase. This supports the findings observed through spatial analysis. According to the results in Table 7, Cr levels are not significantly related to particle size. This may be a reflection of the association between Cr and coarser grained sediments with heavy minerals capable of holding Cr.

Table 7. Correlations: Metals vs. % Fines

			% Fines	Chromium	Copper	Zinc
Spearman's rho	**% Fines**	**Correlation Coefficient**	1.000	-0.04	.262**	.247**
		Sig. (2-tailed)	.	.520	.000	.000
		N	264	264	264	264

** Correlation is significant at the .01 level (2 tailed)

Another relationship examined was between metal levels and distance. In cases where a single source of metal contamination dominates, with the exception of localized highs in areas of secondary deposition, there is generally a decrease in contaminant levels with increased distance from the source (Luoma, 1990). The values in Table 8 indicate that there is a significant negative correlation between contaminant levels for all three metals tested and distance from the Macaulay Point outfall. Therefore, in general, as distance from the outfall increases, metal levels decrease. The relationship is strongest for Cu and weakest for Cr. Distance was calculated from the Macaulay Point outfall since very few of the samples are likely influenced by the Clover Point outfall based on the dominant bottom currents.

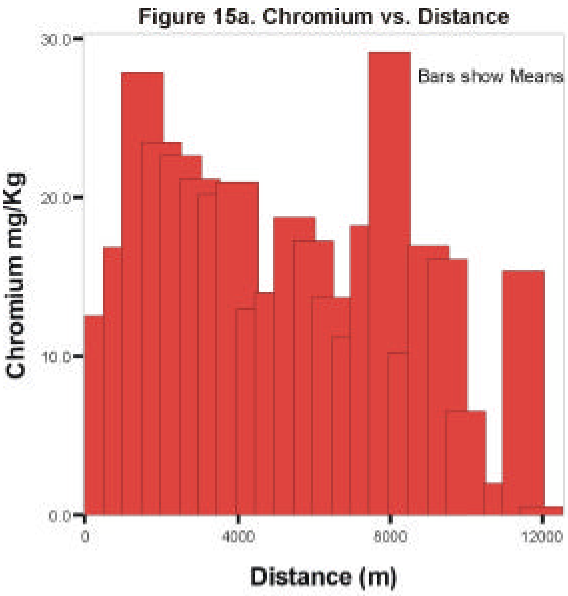
Table 8. Correlations: Metals vs. Distance

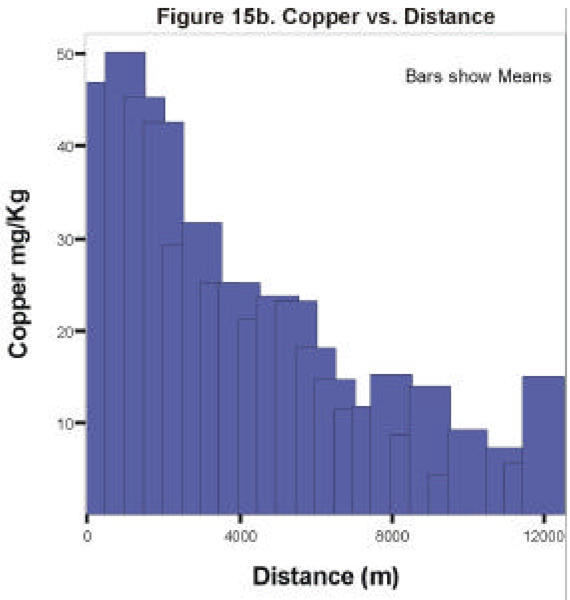
			Distance	Chromium	Copper	Zinc
Spearman's rho	**Distance**	**Correlation Coefficient**	1.000	-.208**	-.493**	-.301**
		Sig. (2-tailed)	.	.001	.000	.000
		N	264	264	264	264

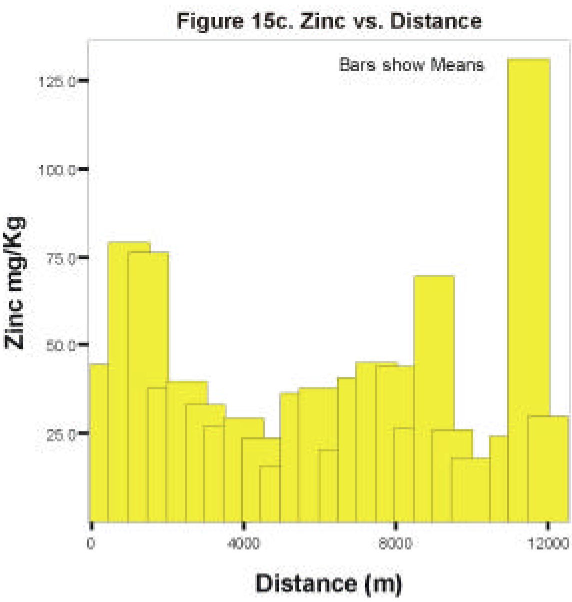
** Correlation is significant at the .01 level (2 tailed)

It should be noted that the Macaulay Point outfall is located in an area dominated by fine sediments, with coarser sediments increasing with distance from the outfall. It is likely that this has an influence on the correlation results given the demonstrated association between metals and sediment grain-size. This would also account for the relatively weak correlation between Cr and distance, based on the potential for Cr to associate with coarser sediment fractions. Figure 15 illustrates the relationship between each metal and distance from the outfall. The graphs, for Cr, Zn and to a lesser extent Cu, indicate the possibility of secondary contamination, due to transport processes, at varying distances from the outfall where metal levels increase with distance. This supports some of the observations made through spatial analysis.

The final bivariate relationship investigated was between metal levels and direction from the Macaulay Point outfall (Figure 16). Data from the 5 samples in the immediate vicinity of Clover Point were not included in the analysis. The graphs indicate the mean metal level for all samples in each of the 8 directions.







The results in Figure 16 should be interpreted with caution. As indicated by the values in Table 9, the distribution of samples by direction is very uneven, with the vast majority of samples being southwest of the outfall. Also, fine sediments are not evenly distributed throughout the study area. Therefore, this will also affect the results since most of the samples north-west of the outfall are fine sediments, and many samples south and south-west of the outfall are coarser sediments.

Figure 16a. Chromium vs. Direction

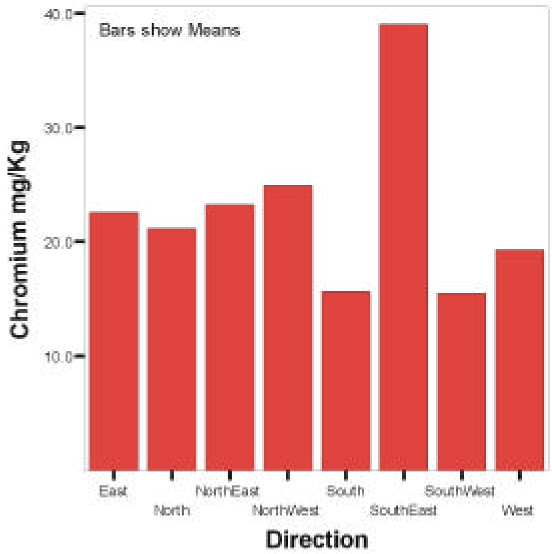


Figure 16b. Copper vs. Direction

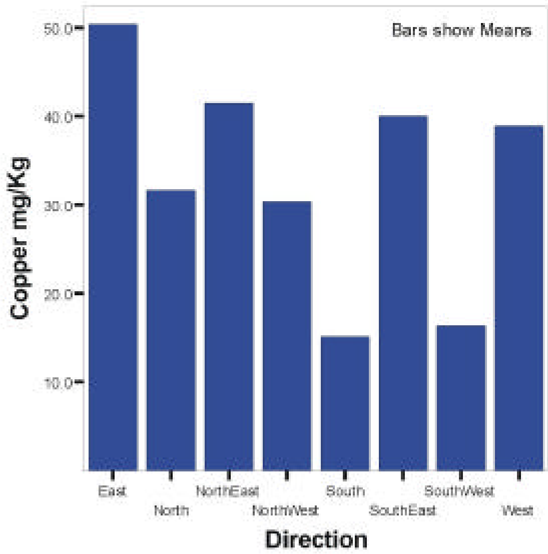


Figure 16c. Zinc vs. Direction

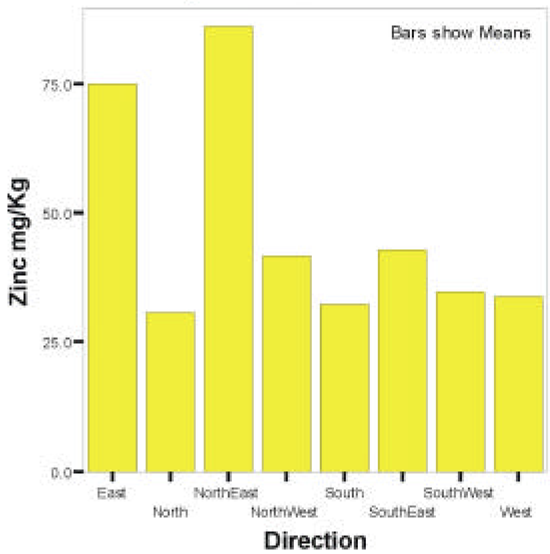


Table 9. Number of Observations per Direction

Direction	N
East	6
North	7
North-East	7
North-West	32
South	31
South-East	3
South-West	124
West	49

Bearing in mind the limitations associated with the results presented in Figure 16, there are some findings worth noting. For both Cr and Cu, mean levels are lowest in the south and southwest directions. This coincides with bottom current data presented in Figure 7a. Chromium results indicate highest mean values in the southeastern direction, which also coincides with bottom current data, however, this result is based on only 3 observations. Copper values also generally correspond to bottom current data, with relatively high values in the east, southeast and western directions. Zinc values also show similarities to bottom current data, exhibiting high levels in the eastern direction. Zinc values for the north, south and southwest directions are relatively similar, and this is also the case for current data. A notable departure from bottom current patterns is the high Zn levels in the northeastern direction. Although less obvious, this is also seen in Cu and Cr levels. The few samples northeast of the Macaulay Point outfall are near the entrance to Victoria Harbour. This portion of the study area overlaps with a sediment transport investigation conducted by GeoSea Consulting. According to findings in the GeoSea report, there is sediment transport occurring in the northeastern direction (from the Macaulay outfall) near the entrance of Victoria Harbour (GeoSea, 1999). This may explain the discrepancy between observed metal levels and bottom current data.

Multivariate Analysis

Principal components analysis (PCA) is a data reduction technique used to identify principal components (PCs), or underlying factors, that are likely to explain the distribution of environmental variables (Facchinelli et al., 2001; Brakstad, 1992). PCA has been widely used to identify sources of metal contamination in sediments (Spencer, 2002; Birch et al., 2001; Simeonov et al., 2000; Salman and Abu Ruka'h, 1999; Ruiz et al., 1998; Emmerson et al., 1997; Negrel, 1997; Huang et al., 1994; EVS, 1992b).

In an attempt to identify the likely source of metal contamination in Victoria Bight, contaminant data were subject to PCA in two transformations. The first was a log transformation, and the second was a log transformation normalized to percent fines. PCA was conducted in three steps. The first was to examine if any correlation existed between Cr, Cu and Zn. The data were then subject to tests to determine their suitability for PCA. Finally, PCs were identified to explain variability in the data. The components that accounted for the majority of the variability were extracted, and how well each metal was explained by those components was indicated.

PCA: Log Transformed Data

Analysis indicates that all three metals tested are significantly, positively related to each other (Table 10). This correlation between metals is often an indication that they come from the same source (Luoma, 1990).

Table 10. Correlation Between Log Transformed Metals

		Log Cr	Log Cu	Log Zn
Correlation	**Log Cr**	1.000	.157	.147
	Log Cu	.157	1.000	.206
	Log Zn	.147	.206	1.000
Sig. (1-tailed)	**Log Cr**		.005	.008
	Log Cu	.005		.000
	Log Zn	.008	.000	

Determinant = .921

The data suitability test results, for the log-transformed data, are displayed in Table 11. The KMO value is greater than 0.50, therefore the PCA is likely to be useful in explaining the data. The significance value related to the Bartlett's test is less than 0.05, indicating that there is a significant relationship between the variables (metals).

Table 11. Data Suitability Test: Log Metals

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.572
Bartlett's Test of Sphericity	**Approx. Chi-Square**	21.468
	df	3
	Sig.	.000

All of the variance in the data is explained by three PCs (Table 12). Of the three PCs identified, the first PC, accounting for 44.7% of the variability in the data, was extracted. The amount of variability for each metal explained by PC 1 is shown in Table 13. All three metals loaded on the same PC. This indicates that it is reasonable to believe that all three metals are from the same source. It should be noted however, that while significant, the correlations in Table 10, the variance explained by PC 1, and the level of variable loading on the extracted component are all fairly low. This is likely due to the effects of variable grain-size (Birch et al., 2001).

Table 12. Total Variance Explained: Log Metals

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.341	44.693	44.693	1.341	44.693	44.693
2	.865	28.841	73.534			
3	.794	26.466	100.000			

Extraction Method: Principal Component Analysis.

Table 13. Extracted Components: Log Metals

	Component
	1
Log Cr	.617
Log Cu	.698
Log Zn	.687

Extraction Method: Principal Component Analysis.
1 component extracted.

PCA: Log Transformed Data Normalized to Percent Fines

Data normalized to percent fines were also subject to PCA. As noted by Birch et al. (2001), removing the effects of gain-size is particularly useful when attempting to identify sources of metal contamination in marine environments where there is a high degree of variability in sediment characteristics. The correlation between the three metals tested is far stronger having accounted for the effects of grain-size. The values in Table 14 indicate that all three metals are almost perfectly positively correlated, further supporting the hypothesis that all three contaminants originate at the same source.

Table 14. Correlation Between Normalized Log Metals

		Cr Norm	Cu Norm	Zn Norm
Correlation	Cr Norm	1.000	.927	.850
	Cu Norm	.927	1.000	.849
	Zn Norm	.850	.849	1.000
Sig. (1-tailed)	Cr Norm		.000	.000
	Cu Norm	.000		.000
	Zn Norm	.000	.000	

Determinant = 3.523E-02

Again, the data suitability tests indicate that PCA will be useful in explaining the variability in the data, and that the variables are related to each other (Table 15). As with the correlation results, the KMO value for the normalized data is higher than that for the non-normalized data, indicating a relative increase in the ‘usefulness’ of the results.

Table 15. Data Suitability Test: Normalized Log Metals

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		.757
Bartlett's Test of Sphericity	**Approx. Chi-Square**	867.145
	df	3
	Sig.	.000

PCA of the data resulted in the identification of three PCs (Table 16). The first PC, which accounts for 91.7% of the variability in the data, was extracted. Variable loadings on the extracted PC were far stronger than those for non-normalized data, accounting for almost 100% of the variability in each of the metals (Table 17). This is a strong indication that the Cr, Cu and Zn found in the sediments of Victoria Bight are originating at the same source.

Table 16. Total Variance Explained: Normalized Log Metals

Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**		
	Total	**% of Variance**	**Cumulative %**	**Total**	**% of Variance**	**Cumulative %**
1	2.751	91.711	91.711	2.751	91.711	91.711
2	.176	5.862	97.573			
3	7.281E-02	2.427	100.000			

Extraction Method: Principal Component Analysis.

Table 17. Extracted Components: Normalized Log Metals

	Component
	1
Norm Cr	.967
Norm Cu	.967
Norm Zn	.938

Extraction Method: Principal Component Analysis.
1 component extracted.

Based on the observations and findings of spatial and statistical analyses, it is likely that the primary source of metal contamination in Victoria Bight is the Macaulay Point outfall.

6.4 Sediment Contamination and Sustainable Development

6.4.1 Sustainable Development

While there are numerous definitions of sustainable development (SD), in its simplest form (simplest in terms of definition, certainly not in terms of implementation) it is essentially a reconciliation of economic, social and ecological imperatives (Dale and Hill, 1996). While the enormity of how to achieve sustainable development is well beyond the scope of this research, there are a number of key components, or underlying principles, of SD that are relevant to sewage related sediment contamination.

Biodiversity

The health and well-being of humans are linked and ultimately dependent on ecological health. The loss of biodiversity at the species and ecosystem levels is one of the greatest threats to society (Dale, 2001).

The ecosystem is comprised of four main components; air, water, land and biota. Through a number of pathways each of these components are interconnected. The contamination of any of these components may lead to the contamination of another component. Sediments are a key element of the marine ecosystem. Because of their physio-chemical properties, sediments are a sink for contaminants, and subsequently a source of contamination for the ecosystem components to which they are linked. Significant contamination of sediments may lead to species loss (Burton, 2002; Luoma, 1990).

The potential impacts of sediment related contamination is wide ranging. Deleterious effects have been observed throughout the biota continuum; from benthic communities, via direct exposure, to upper trophic levels (aquatic and terrestrial), through food-web contamination (Burton, 2002). In marine environments, a key indicator of a severely polluted or stressed environment is when biomass becomes greater than biodiversity. This is caused by a replacement of many specialist species with a few tolerant opportunistic species. This transformation is generally characterized by a reduction in echinoderms and arthropods and an increase in polychaetes and molluscs (Anderlini and Wear, 1992; Langston, 1990). Studies by EVS Consultants indicate that the situation described above has been observed near the outfalls (EVS, 1992a,b). In addition, during the sampling portion of this research, polychaetes -- specifically annelids, were frequently recovered with sediment grab samples, and in a number of cases near the Clover Point outfall, no sediment could be recovered because of thick mussel beds.

The EVS reports describe the flourishing mussel and worm communities around the outfalls as healthy, and indicative of low toxicity (EVS, 1992a,b). While the report concedes that biomass is greater than biodiversity, around the outfalls, it does not discuss the potential implications of this finding. The report also fails to address the possibility that fauna found near the outfalls may have developed coping mechanisms allowing them to thrive in toxic environments. Research on mussels has found that exposure to metals can lead to the production of metallothionein (MT), and other metal-binding proteins, allowing such organisms to tolerate metal induced toxicity. Therefore, rather than using mussel communities as an indication of low toxicity, the measure of MT production has been identified as a useful measure of contaminant related stress (Langston, 1990).

Species that are intolerant to metal contamination can be adversely affected in a number of ways. Impacts on reproduction and growth can impair the survival of individuals, and affect populations and communities. Research has found that Cu can be acutely toxic to microalgae at levels between 0.19µg l^{-1} and 0.30µg l^{-1} and that Zn can reduce growth at 15µg l^{-1} to 20µg l^{-1}. Studies have also demonstrated impaired growth of dinoflagellate assemblages resulting from Cu levels of 15µg l^{-1}. Furthermore, research has shown that recruitment can also be affected by metal contamination. This phenomenon has been observed in clams (*Macoma bathilica*), which have demonstrated an avoidance of contaminated sites (Langston, 1990).

Negative impacts related to metal contamination do not necessarily result from direct toxicity. For example, contaminant-related changes to phytoplankton communities may have serious consequences for higher trophic levels. A change in the phytoplankton community structure can lead to a reduction in preferred prey species, and ultimately the loss of higher trophic species in those communities. It is possible that the indirect effects triggered by the loss of sensitive species have a much more significant impact on marine communities than indicated by toxicity tests with an individual species (Langston, 1990).

Scientific Uncertainty & the Precautionary Principle

One of the underlying philosophies of SD is the precautionary principle. Under this paradigm, it is not acceptable to use scientific uncertainty as justification to postpone action. The phrase 'better safe than sorry' is a good representation of the ideals behind the precautionary principle. Under the current framework decision-makers require scientific certainty, and more specifically proof of harm to justify actions to alter or eliminate a potentially harmful activity. This certainly applies to the issue of sewage disposal in Victoria. Ecological systems are immensely complex, and while science has made great progress in understanding natural systems, there is still far more that is unknown, than is known.

Toxic metals are continuously released into the environment, many of them contaminating sediments. While some of the effects resulting from sediment contamination have been documented, the true extent of short and long-term risks to biota and humans is largely unresolved (Burton, 2002; Luoma, 1990). Most of the toxicity studies have not addressed the implications of in situ short and long-term exposures representative of the real world. Rather, the data only represent acute short-term effects (Burton, 2002).

Much of the toxicity research conducted is performed on surrogate species. The problem that results from studies on a particular species are not necessarily indicative of the response of different species, even within the same genus. Furthermore, with increased taxonomic difference comes increased probability that research findings will not reflect true response (Chapman, 1991). Another inadequacy of toxicity research is the frequent failure to account for compounding effects. For example, research on the impacts of sewage discharge in the Fraser River Estuary revealed that although Hg, Cu and Zn concentrations were not toxic to adult clams (*Macoma bathilica*), their combined effect resulted in juvenile mortality and prevented settlement near the outfall (Langston, 1990). Toxicity testing data are the basis for many environmental guidelines, including those developed for sediments. Unfortunately guidelines developed from these data do not account for indirect effects such as bioaccumulation and transfer to higher trophic levels (Burton, 2002). All of the metals studied in this research can potentially bioaccumulate in certain marine organisms. Cu and Zn are essential to certain biological functions, and organisms have developed mechanisms that regulate essential metals. However, depending on environmental levels, regulatory mechanisms may be incapable of coping with uptake levels leading to bioaccumulation (Rainbow, 1990).

6.4.2 Sediment Quality Guidelines

All human activity has an impact on the environment. For a very long time, the consequences of human activity were not recognized. Eventually, it became evident that many anthropogenic activities were harmful to ecological systems. A mechanism was necessary to link scientific findings to policies and regulations. Environmental guidelines have been developed to monitor human impact on the environment, and to gauge the quality of the environment. Over the last decade the importance of sediment quality has gained a great deal of attention, and a number of sediment quality guidelines (SQGs) have been developed in consequence.

Empirical data have been used to develop two general sets of SQGs based on threshold levels. The first, 'threshold level' SQGs, define toxic levels below which effects occur infrequently (LEL, TEL, ERL, MET, TEC); and the second, 'effect level' SQGs, define levels at which effects are expected to occur (AET, SEL, PEL, ERM, TET, PEC). One of the earliest empirically-based SQGs were AETs developed by the WDOE for sediments in Puget Sound. Unlike other 'effect level' SQGs, AETs are based on significant effects always occurring and are therefore under-protective (Burton, 2002; Birch et al., 2001). As noted in Section 2.2, the AETs developed by the WDOE are currently used by the CRD to evaluate the sediments in Victoria Bight, despite their inherent unsuitability (see Section 2.2).

The term 'contamination' is defined as the introduction of unwanted substances, however; the term takes on an entirely new and subjective definition when used in environmental assessment. For the purposes of environmental management, sediment is only considered contaminated when it surpasses sediment quality guidelines (SQGs). For this reason, understanding how the SQGs used were developed, and for what purpose, is of critical importance when interpreting environmental data. The SQGs used by the CRD are 'effect level' AETs. The guidelines for the three metals tested in this research are shown in Table 18.

Table 18. CRD/WDOE Sediment Quality Guidelines

	Chromium µg g^{-1}	Copper µg g^{-1}	Zinc µg g^{-1}
SQG	260.0	390.0	410.0

Results reported by EVS Consultants indicate that levels for Cr, Cu and Zn were all highest at the Macaulay Point outfall sample station (Figure 2). None of the samples surpassed the AET SQGs with maximum values for Cr, Cu and Zn reported as 59.4µg g^{-1}, 197.0µg g^{-1} and 197.7µg g^{-1} respectively (EVS, 1992b). Therefore, based on the SQGs in place, the CRD suggested that there is no evidence of metal contamination from Cr, Cu or Zinc. To demonstrate the tremendous influence particular SQGs have regarding policy and decision-making; the contaminant data from this research were mapped based on various SQGs (Figures 17, 18, 19). As the figures indicate, the more protective the SQG, the greater the extent of contamination – in the regulatory sense.

By default, the more protective SQGs (LEL, TEL etc.) do a better job of accounting for chronic sub-lethal effects, as opposed to AETs that are largely based on acute effects. Ironically, proponents of the CRD's LWMP argue that the discharge of untreated waste is not a problem because of dilution and the self-cleansing properties of the receiving environment. As noted by Langston (1990), this type of environment simply leads to a much larger area subject to moderate levels of contamination, a situation where the monitoring of chronic sub-lethal effects is far more appropriate to evaluate harm.

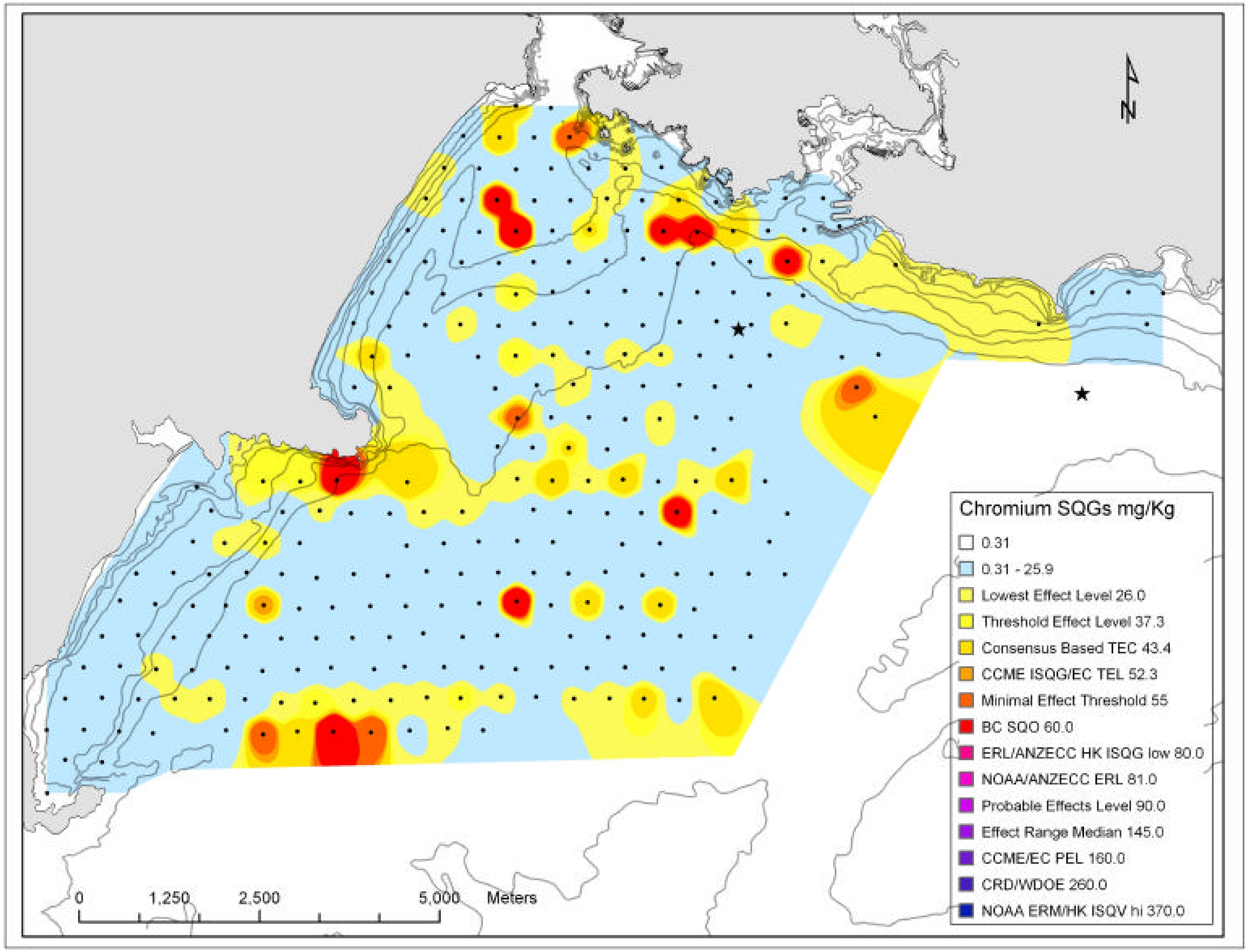


Figure 17. Chromium Sediment Quality Guidelines

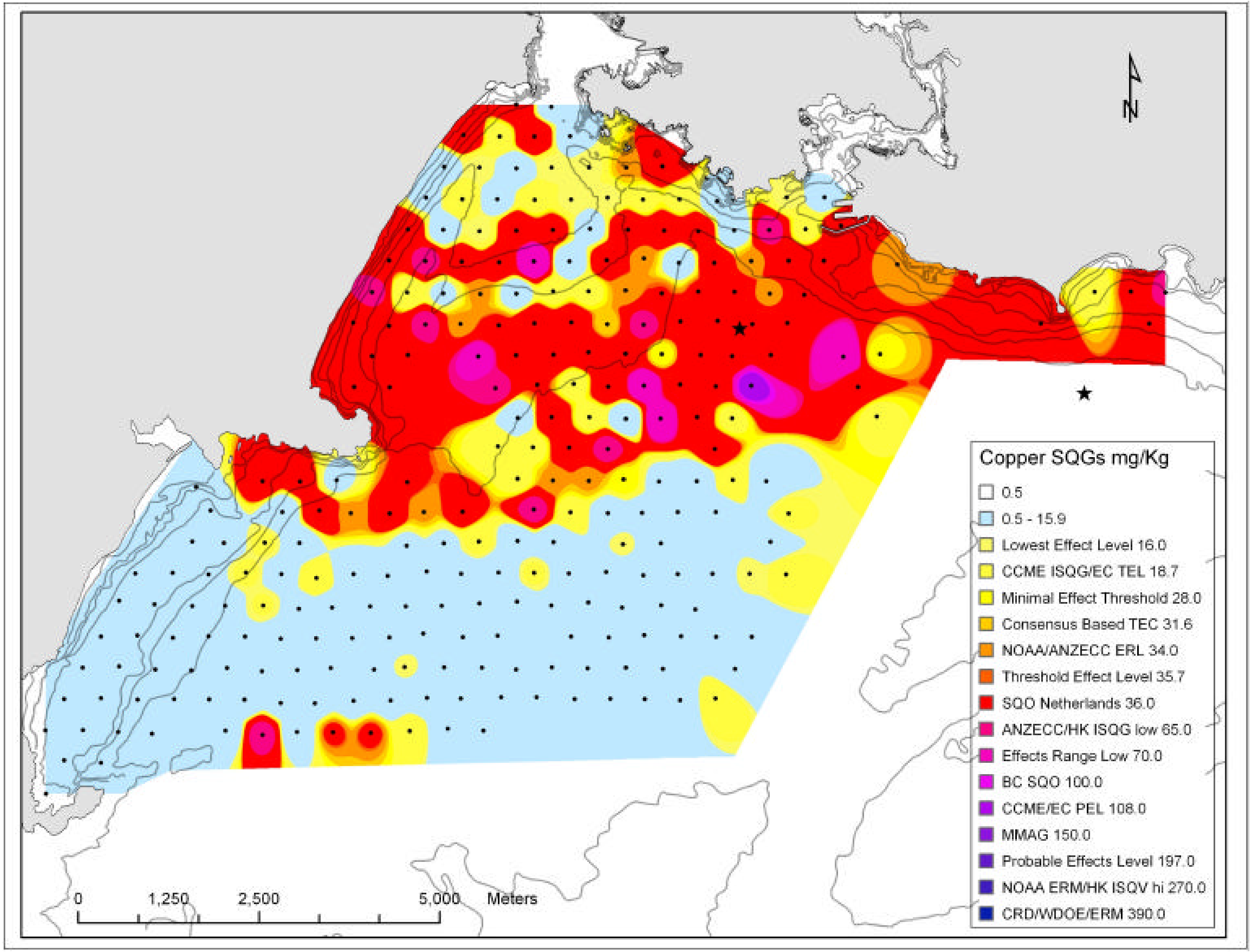


Figure 18. Copper Sediment Quality Guidelines

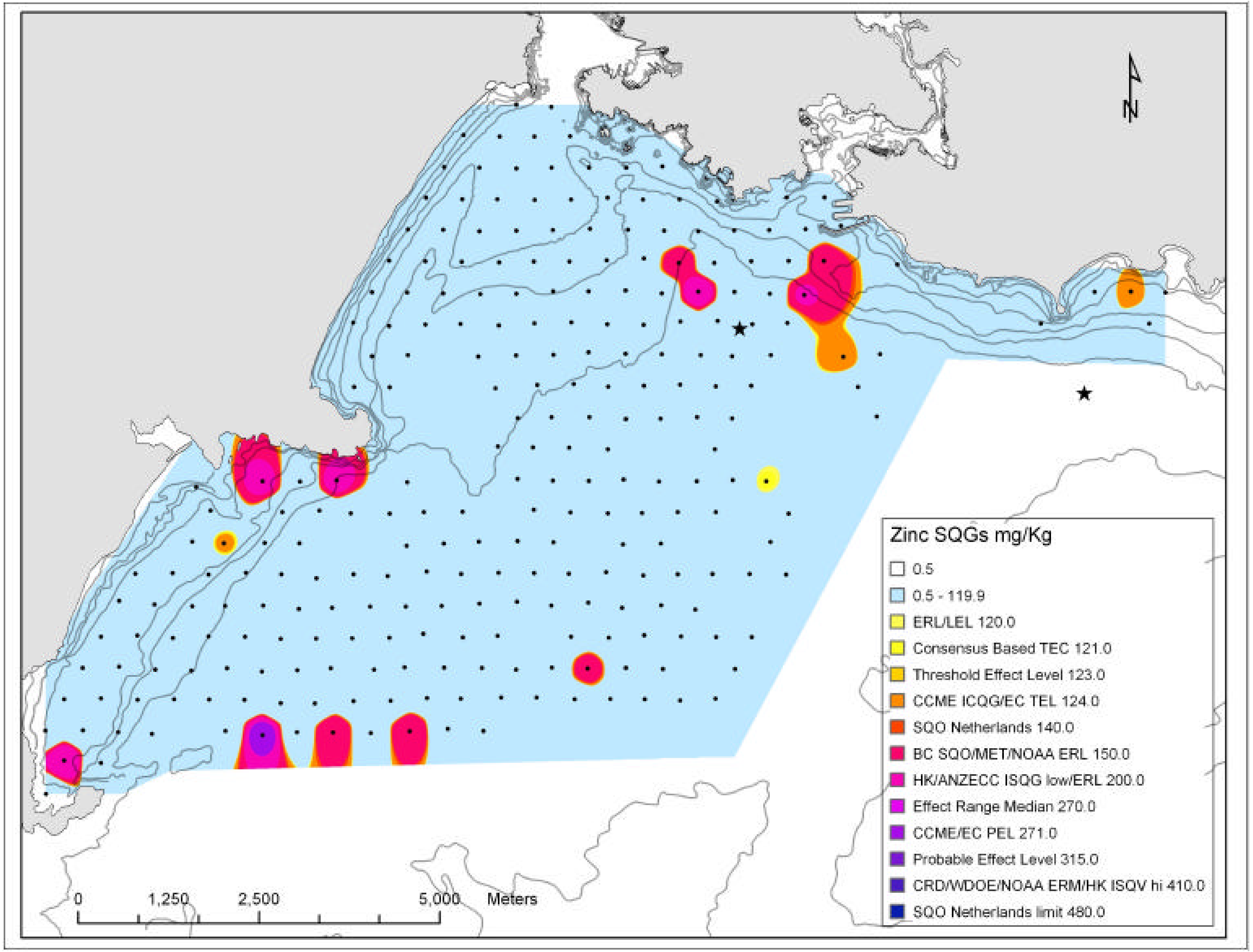


Figure 19. Zinc Sediment Quality Guidelines

There are some implications to consider when using 'effect level' SQGs (SEL, PEL etc.), particularly the under-protective AETs. Research indicates that 'effect level' SQG values are significantly above realistic environmental levels. This is particularly applicable for the majority of coastal and off-shore marine environments; where dilution can lead to a broad area of moderate contamination. The end result, when using 'effect level' SQGs in coastal environments, is the appearance that impacts are restricted to the immediate area of the contaminant source – while the potential for chronic damage at the ecosystem level is unaccounted for (Langston, 1990). This precisely reflects the current situation in Victoria Bight, where the CRD states that impacts are restricted to the immediate vicinity of the outfalls (Taylor et al., 1998; EVS, 1992b).

Based on the discussion above, it is clear that the CRD's current LWMP does not conform to the principles of sustainable development. The loss of biodiversity and subsequent damage at various trophic levels resulting from sewage contamination is a significant possibility. Furthermore, there is a great deal of uncertainty, in regard to both short and long-term chronic effects of sediment contamination, yet SQGs focused on immediate acute effects are used. In order to become compliant with SD, the CRD's LWMP would have to undergo a number of changes: more protective SQGs would need to be implemented, and the amount of contaminants discharged from the outfalls would have to be minimized. There are two main methods for reducing sewage contaminant loads: source control and treatment. The CRD suggests that its source control program is sufficient, yet a report by the SLDF states that CRD documents indicate that there has been no measurable reduction in contaminant load since the implementation of the source control program (SLDF, 1999). Also, Cu has been established as one of the worst marine contaminants and it is unlikely that source control alone will sufficiently reduce Cu loadings since much of the current piping used in plumbing is Cu. Source control alone also fails to address issues of non-compliance, and accidental releases. To truly comply with SD, and minimize the amount of contaminants being discharged, the CRD would have to incorporate both source control programs and waste treatment facilities.

7.0 Conclusions

The research conducted for this study was carried out to accomplish the following:

- Determine the spatial distribution and level of metal contamination in surface sediments in Victoria Bight, particularly Cr, Cu and Zn
- Determine if the sewage outfalls are the likely source of metal contamination
- Evaluate the current LWMP from a sustainable development perspective

Using GIS software to perform spatial analysis, the distribution of metal concentrations in sediments in Victoria Bight was determined. Elevated metal levels were consistently identified in three areas within the study area. The largest area is in the northern region of the study area, near Royal Roads and extending southward to Albert Head. The second zone of accumulation is immediately south of Albert Head, and the third area is at the southern extent of the study area, immediately east of William Head. This may indicate that contamination is occurring beyond Victoria Bight.

The physical characteristics of the receiving environment, along with observations made during spatial analysis, were used in conjunction with statistical analyses to investigate the source of elevated metal concentrations in the study area. Based on weight-of-evidence, it is probable that the Macaulay Point outfall is the primary source of elevated sediment metal levels in Victoria Bight.

The CRD's current LWMP does not conform to the principles of sustainable development. It is particularly lacking in the protection of biodiversity, and adherence to the precautionary principle. Two major changes are necessary to rectify these shortcomings. First, the CRD would have to use far more protective SQGs such as LELs instead of AETs. Second, the CRD would have to implement an effective source control program, and install waste treatment facilities, to minimize the amount of contaminants being discharged into the receiving environment.

While this research has filled some of the knowledge gaps related to the sewage issue in Victoria, it also serves to identify areas that require further research. Given the relationship between contaminants, fine particles and depositional areas, a more complete understanding of the dynamic behaviour of sediments in all of Victoria Bight could prove very beneficial to environmental managers. In addition, this study is limited in terms of chemical analyses. Analysis for a full suite of contaminants could potentially provide a better understanding of the over all level of sediment contamination in Victoria Bight. Finally, at a far broader level, this study has revealed that a great deal of research is necessary to develop effective means of conveying the importance of sustainable development to scientists and decision-makers alike.

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