A KNOWLEDGE-BASED SPATIAL DECISION SUPPORT SYSTEM (SDSS) FOR COASTAL ZONE OIL SPILL RESPONSE IN ANAKTALAK BAY, LABRADOR

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A KNOWLEDGE-BASED SPATIAL DECISION SUPPORT SYSTEM (SDSS) FOR COASTAL ZONE OIL SPILL RESPONSE IN ANAKTALAK BAY, LABRADOR

By

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ABSTRACT

Coordinating a successful oil spill response operation requires fast and reliable data access, expert guidance, and efficient communication of information. In this thesis, the theory, development and implementation of prototype oil spill response Spatial Decision Support System (SDSS) are discussed in detail. In order to aid decision-makers and response personnel during the initial hours of a coastal zone oil spill, this SDSS integrates the analysis, storage and visualization functions of a Geographic Information System (GIS), with the logical reasoning capabilities of an expert system.

The prototype SDSS is developed through three main phases: (1) creation of the oil spill response expert system, (2) modification of the GIS environment and automation of GIS analysis, and (3) integration of the GIS and the expert system through a graphical user interface (GUI). The functionality of the final system is tested by means of four annotated examples, each representing a different oil spill scenario. Results of the sample scenarios demonstrate the successful transfer of knowledge and data between the GIS, the expert system and the user, and indicate that a SDSS can provide a feasible alternative to the traditional oil spill response decision-making process.

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LIST OF ABBREVIATIONS

CCG – Canadian Coast Guard
ESI – Environmental Sensitivity Index
GIS – Geographic Information System
NAD – North American Datum
NOAA – Notional Ocean and Atmospheric Administration
ORI – Oil Residence Index
SDSS – Spatial Decision Support System
VBNC – Voisey's Bay Nickel Company

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CHAPTER 1

Introduction

Offshore oil developments, a steady increase in marine shipping traffic, and a continued heavy dependence on petroleum products contribute to the ever-persistent risk of marine oil spills. Disastrous spills such as that of the Exxon Valdez in 1989, and the more recent Prestige, in November 2002, demonstrate the potentially catastrophic consequences of these events. The resulting damages to marine and coastal environments can be extensive and long-lasting, making the rapid implementation of protection and treatment operations essential. Establishing practical oil spill response measures, therefore, is fundamental for the protection of marine and coastal environments (Sorensen, 1995).

Successful oil spill response is defined by quick and efficient actions to minimize the effects of any threats generated by an oil spill. The early stages of a response plan are particularly crucial, and can greatly influence the overall effectiveness of cleanup efforts. Many of these initial processes, however, involve tedious tasks, such as sifting through cumbersome oil spill response manuals, which can often unnecessarily delay response proceedings, thereby providing more opportunity for greater damages to ensue.

When an oil spill threatens or damages a coastal zone, as opposed to open ocean, the potential for negative consequences increases substantially. The coastal zone is a unique environment exhibiting a highly dynamic and intricate structure, which can be extremely sensitive to oil spill pollution. Numerous interrelated factors including ecological, geomorphological, and anthropogenic attributes of a coastal zone must be considered before determining suitable response proceedings.

The physical and biological variation that exists within coastal environments, even at a very small scale, can complicate the process of determining the appropriate oil spill response procedures. Specific strategies and techniques are required based on the particular characteristics of an affected coastal area. The behaviour and movement of the spill, the form and function of the coastline, and the types of resources associated with both the land and water components of the coastal zone are the primary determinants. Such detailed information pertaining to affected marine and coastal areas can be difficult to obtain; and delayed access to information is one of the key factors, which can impede oil spill response proceedings.

Efforts have been made over the past decade to increase the efficiency of oil spill response operations, particularly with regards to collecting environmental data, accessing information, and improving oil spill behaviour models (Harper *et al.*, 1991; Owens and Dewis, 1995; Green, 1996). There is a recognized need to decrease reliance on the many time-consuming methods currently being used to determine appropriate response strategies. Several key problems pertain to the acquisition of up-to-date environmental data, the ability to quickly access oil spill response knowledge, and the rapid identification of threatened areas. It is this initially slow process of data access and decision-making that inhibits the effectiveness of many response operations (Green, 1996).

The development of an oil spill response Spatial Decision Support System (SDSS) offers a solution to many of the problems currently impeding traditional response procedures. A SDSS is an integrated computer system designed to provide the user with the knowledge, data, and analysis capabilities necessary to solve complex spatial problems (Densham, 1991). Through a user-friendly environment, information can be input, manipulated, and output in an easily comprehensible format.

In the context of oil spill response, a SDSS would serve to process data and information concerning a specifically-defined oil spill event, and produce reports describing suggested response strategies and techniques for individual areas of coastline. The SDSS would contain an extensive spatial database comprised of location-specific information, such as coastal attributes; and would also contain the needed tools to evaluate the data and provide relevant solutions to a given oil spill problem.

The primary goal of this research is to develop an oil spill response SDSS through the integration of a Geographic Information System (GIS) and an expert system. A GIS is a computer system capable of storing, analyzing, manipulating, and representing complex spatial data (Burrough, 1992), while an expert system is a computer program that attempts to capture the knowledge and experience of human experts for the purpose of solving problems in a given domain (Nikolopoulos, 1997). The integration of these two systems will produce a problem-solving tool capable of performing both hard data analysis and logical reasoning.

The combination of data and knowledge is fundamental for solving many real-world problems, including those in the domain of oil spill response. Many aspects of oil spill response are numerically-based, including the calculation of oil spill trajectories; whereas the process of selecting appropriate response strategies relies on a superior understanding of the situation and accumulated experience in the field. In the event of an oil spill, a SDSS should be able to integrate and evaluate these two different forms of information in order to identify the appropriate response options.

A functional SDSS will provide improved data access and analysis capabilities, in addition to providing direct access to knowledge and advice that may otherwise be unavailable (Zhu *et al.*, 1998). The resulting information will promote improved response efficiency, which will subsequently ensure a prompt and effective reaction to a potentially disastrous event.

1.2 Statement of Objectives

The goal of my thesis is to develop a prototype knowledge-based SDSS for emergency coastal zone oil spill response. The key to developing the oil spill response SDSS, and the main objective of my research, is to establish a viable connection between the knowledge and the data within the SDSS. This linkage is accomplished by integrating the expert system and the GIS.

A comprehensive Graphical User Interface (GUI) is constructed to handle the transfer of information between these two main components of the SDSS. The GUI acts as a communication node, which imports and exports data from the expert system and the GIS, and more notably is used to properly format this information, thereby enabling successful and efficient communication between the two systems. Additionally, the GUI serves as a communication node between the SDSS and the user. The interface is used to collect and organize output from the expert system and the GIS, in order to present the user with a thorough account of the oil spill event, and a detailed explanation of appropriate response options.

Secondary objectives of this research include (1) building a functional oil spill response expert system and organizing the associated knowledge in the form of "action tables"; and (2) automating multiple GIS functions, modifying the GIS environment, and developing an oil spill model within the GIS.

Action tables are a highly efficient method of handling a large quantity of rules or a knowledge base (see Section 2.3.1). The information contained within the action tables integrates the spatial data output from the GIS with user input and expert knowledge, in order to identify solutions to an oil spill problem. The knowledge and data is combined in such a manner that emulates the reasoning process of a real-life expert, and subsequently generates viable output.

Modifications are made to the GIS environment as a means of establishing a spatial analysis system that is transparent to the user. New functions are designed to handle the processing requirements of SDSS, including the oil spill model, which calculates the spread of an oil spill based on user input and spatial variables contained in the GIS database.

The objectives of my research are met through the completion of four key steps, the first of which is the construction of an oil spill response expert system. This system is used to evaluate the data and knowledge, and produce a series of logical conclusions in the form of user-friendly output. As is often the case with real-life expert assessment, much of the reasoning contained within the expert system is heuristic, and therefore based on rules and logical inference rather than numerical algorithms (Durkin, 1994).

The second step in constructing the SDSS is to adapt existing GIS software to perform the required analysis procedures, output data for the expert system analysis, and as well, provide useful map output. The GIS acts as an extensive spatial database, containing detailed location-specific information. The GIS data forms the basis for the spatial analysis functions that are used to evaluate the spread and influence of the oil spill. Normally, the spatial analysis functions of a GIS would be beyond the capabilities of an inexperienced user. However, in order to develop a successful SDSS, all operations must be user-friendly. Therefore, complex analytical and output operations will occur with only minimal user input, and will not require the user to perform any tasks beyond their capabilities.

The third step in this research is to integrate the expert system and the GIS into a single functioning unit. This step is fundamental in the development of an effective SDSS. A seamless, user-friendly interface will promote quick and easy access to the advice or information that is necessary in solving the given problem (Densham, 1991). The user should never encounter the underlying complexities of the system, and should not be delayed by unnecessary complications, but instead should be able to focus on the problem at hand.

The final step of this research is to evaluate the effectiveness of the SDSS, through the assessment of several trial oil spill situations. This process will provide answers to questions concerning the overall functionality of the system. Questions essential to my research include:

(1) Can oil spill response knowledge and data be combined effectively through the integration of an expert system and a GIS?

(2) Does the GUI serve to effectively integrate the expert system and the GIS?

(3) Does the SDSS produce the required information? Is it useful for coastal zone oil spill response decision-making?

(4) Can inexperienced individuals use the SDSS? Is it straightforward and user-friendly? Is the SDSS output relevant and easy to understand?

(5) Is the system fast and efficient?

(6) Does the SDSS offer advantages over the traditional methods of oil spill response decision-making?

CHAPTER 2

Background Information and Literature Review

In the year 2000, it was estimated that approximately 6.4 million tons of oil was being discharged into the oceans every year (Clark, 2001). As a reaction to this ever-present threat of marine and coastal oil spills, efforts to prevent and reduce oil pollution have intensified in recent years. The ultimate solution would involve the complete elimination of potential oil spill sources. However, a continued worldwide increase in the rates of oil production and consumption suggest that this option is not yet feasible. In fact, according to trends in energy usage, petroleum exploitation is not likely to decrease significantly anytime in the near future (Fingas, 2001).

For now, developing and improving preventative measures is the main option for reducing marine and coastal oil pollution. Preventative measures, such as improved ship and tanker construction, expert navigation, and proper maintenance of equipment, can minimize the potential for oil spills. Still, despite best efforts, it is currently impossible to completely prevent oil from entering the ocean environment (Etkin, 1990). As long as society continues its dependency on petroleum products, oil spills will occur, and effective preparation is essential (Fingas, 2001).

Contingency plans are the most prominent form of oil spill response preparation. These plans consist of written response guidelines that describe the established procedures to follow in the event of a spill (Doerffer, 1992). The purpose of these plans is to enable rapid mobilization of response operations, and improve the results of protection and cleanup efforts. However, contingency plans are still lacking in many aspects, particularly in terms of maintaining up-to-date information and providing situation-specific data. As a result, the field of marine oil spill response is rapidly embracing the technology of Geographic Information Systems (GIS) in order to compensate for the inadequacies of traditional methods (Sorensen, 1995).

GIS offers substantial opportunities for improving oil spill response operations (Howlett and Bradstreet, 1996). According to Green (1996), the key to efficient response planning lies in the ability to reliably, timely, and cost-effectively acquire data and information; and these goals can be accomplished by exploiting the comprehensive storage and analysis tools provided by existing GIS programs. In combination with additional software modules, such as an expert system, a GIS can be used to develop a highly effective oil spill response SDSS (Armstrong *et al.*, 1990; Densham, 1991; Ji *et al.*, 1992). Such a SDSS would assist response personnel with the identification of potential risks and provide essential advice concerning the protection and treatment of coastal areas.

In this chapter I review background research which is relevant to the development of an oil spill response SDSS, beginning with a brief introduction to coastal zone oil spill response. The subjects of GIS and Expert Systems are discussed individually and in combination with specific reference to oil spill response. Finally, Spatial Decision Supports Systems are discussed with regards to their structure, the requirements for an effective SDSS, and recent applications of SDSSs for coastal zone management and oil spill response.

2.1 Coastal Zone Oil Spill Response

Over the past several decades, marine oil spill response has become a well-developed field. Extensive literature has been published on the subject, including texts on the basics of oil spill response (Doerffer, 1992) and a multitude of journal articles and technical papers covering a wide range of technical issues (Fingas and Tennyson, 1991; Liddell, *et* al., 1994; Rodríguez and Brebbia, 2000; Brebbia, 2001). Breuel (1981), Doerffer (1992), and Fingas (2001) have written texts concerning the fundamentals of spill response, in which they discuss tools and established techniques, in addition to comprehensive explanations of oil spill, oceanographic, and coastal dynamics. Precise information is also contained in spill response manuals such as those produced by CONCAWE (1981) or Owens (1995), which provide concise and practical descriptions of response options.

Oil spill response manuals are numerous; some are region-specific (Owens *et al.*, 1998), while others are developed for broader usage; however, documented response techniques and procedures vary little from source to source. Cramer *et al.* (1991) discuss a detailed response manual for the coastline of British Columbia, which provides guidelines for the assessment, protection, and cleanup of oiled shorelines. The primary goal of this comprehensive manual, as with most contingency plans, is to "provide the On-Scene Coordinator and his or her staff with a systematic, easy-to-apply methodology that can be used to assess the threat of an oil spill and to select the most appropriate shoreline protection and cleanup techniques." This reference document and field guide was developed to promote effective and rapid protection and cleanup decision during an oil spill event.

A similar document produced by Owens *et al.* (1998) was developed with the express purpose of providing "circumpolar countries with oil spill response guidance specific to the unique climate and physiographic features of the Arctic environment." This manual is extensive, and provides precise instructions regarding the selection of appropriate response strategies and techniques for varying spill situations.

However, in the event of an oil spill, reference documents, like those described above, provide neither quick nor easy access to the required response knowledge. This weakness is not a result of inadequately prepared information, but instead is due to the cumbersome form in which it is presented. For example, the manual produced by Owens *et al.* (1998) contains over 350 pages of decision-making guidance. The time-consuming activity of browsing such manuals or data documentation can cause serious delays in response-time (Smith and Loza, 1994) during which the situation will likely worsen. As a result, ships, coastal facilities, personnel, and coastal environments may be exposed to increasing hazards and greater damages (Oil Companies International Marine Forum, 1990). These potential consequences reinforce the need for a more reliable form of contingency planning, and improved access to information.

As stated by Green (1996), "little information is readily available to help prevent or minimize the effects of oil spills," despite an obvious need. As a result there have been recent increased efforts to organize oil spill response information and to develop superior methods of evaluating spills. Particular emphasis has been placed on improving the identification of coastal areas and resources, which have been or may be affected by a spill (Sorensen, 1995).

For improvement of coastal inventory analysis, Owens and Sergy (1994) recommend segmenting the coast into geomorphologically distinct segments, or referring to previously segmented maps of the affected area, if available. Cramer *et al.* (1991) also employ coastal segmentation for the identification process. Segmented coastline maps are often developed as a means of pre-spill planning. Data for coastal segment maps can be collected using a variety of methods including aerial photos, aerial videotape surveys, and ground surveys (Cramer *et al.*, 1991; Cormorant Ltd., 1997).

Recently, the benefit of pre-surveying coastlines has been recognized, particularly in regions exhibiting high oil spill risk (Demspey *et al.*, 1995; Cormorant Ltd., 1997; Harper *et al.*, 1991). During a spill situation, this strategy aids oil spill personnel by providing a detailed inventory of coastal resources. The use of coastal sensitivity maps is an equally beneficial approach, whereby coastal areas are examined in advance, in order to determine levels of sensitivity to oil pollution, and potential for oil retention.

A commonly used sensitivity scheme, developed for oil spill evaluations, is known as the Environmental Sensitivity Index (ESI), which distinguish coastal areas based on geomorphological or structural characteristics. Shoreline types are ranked from most to least sensitive, or visa versa, generally on a scale from one to ten (Gundlach, 1991; Michel, 1998). Sensitivity levels indicate a coastal area's susceptibility to damage from oil pollution. More precise sensitivity indexes can be calculated based on a detailed analysis, whereby factors such as biological and human resources are assigned individual sensitivity values, which are subsequently used to calculate a single index value for each unit of coastline (Mosbech *et al.*, 2000).

An Oil Residence Index (ORI) can also be a valuable source of information to oil spill respondents. An ORI is a relative estimate of the potential residence period for oil stranded at the shoreline, and is determined based primarily on level of exposure to wind and wave activity, and substrate type (Mosbech *et al.*, 2000). Values typically range from one to five, representing increasing times of oil residency, from days to months to years (see Table 2.1).

Table 2.1: Oil Residence Index (ORI) ranking based on a combination of shoreline substrate and exposure class (modified from Mosbech *et al.*, 2000 and Cormorant Ltd., 1997).

Substrate	Exposure Level			
	Protected	Semi-Protected	Semi-Exposed	Exposed
Coarse sediment	4	3	1	1
Fine sediment	4	3	1	1
Not classified	4	3	2	1
Rock	4	3	1	1
Rock and coarse sediment	5	4	2	1
Rock and fine sediment	5	4	2	1

ESI and ORI values can be maintained in coastal databases, which have also become a well-accepted means of pre-spill planning. Extensive coastal databases can be associated with coastal areas, whereby ID numbers are used to distinguish segments of coastline (Owens and Sergy, 1994; Owens and Dewis, 1995; Harper *et al.*, 1991). Each section of coastline is characterized by a unique set of attribute values, which represent the geomorphological, ecological and anthropogenic characteristics of the area. The potential of a coastal database can be further enhanced by establishing a link to a Geographic Information System.

2.2 Geographic Information Systems

The earliest Geographic Information Systems (GIS) were developed in the mid- to late-1960s. As discussed by Maguire (1991), there are still many discrepancies concerning the definition of these systems. One of the more widely accepted definitions was provided by Burrough (1986) who describes a GIS as "a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world".

The real growth of GIS began in the 1980s when the availability of commercial GIS substantially improved, thus enabling organizations and individual users to access desktop systems such as ARC/INFO (Coppock and Rhind, 1991). Since that time, the number of potential applications for GIS has grown exponentially (For a detailed history of GIS refer to Coppock and Rhind (1991) or Foresman (1998)).

To date, most successful applications of GIS pertain to land-based issues, which are more suited to the structure of current GIS software. The inability of current commercial systems to effectively handle marine and coastal data types is an ongoing subject of GIS research (Bartlett, 2000).

2.2.1 Coastal Geographic Information Systems

When applying GIS to the coastal zone, the main obstacle is the complexity of a coastline's form and function, which is more difficult to represent then that of land-based features. Bartlett (2000) discusses the many challenges and issues associated with applying GIS technologies to the coastal zone. Of particular concern are the multiple uses and characteristics associated with the shoreline (Fedra and Feoli, 1998). The linear structure often used to depict coastlines is suggestive of an insignificant feature, and does not illustrate the truly complex nature of a coastline. In order to perform more effective analysis of coastal problems using GIS, there is a need for coastlines to be better represented, such that the simplicity of appearance is maintained yet the complexity of their characteristics is also portrayed. With regards to coastal zone management and decision-making, conflicting interests and views of what constitutes the coastal zone should also be addressed within a coastal GIS model. The model should represent conceptual, as well as functional, aspects of the coastal zone (Bartlett, 2000).

Wright and Bartlett (2000) published an in-depth collection of papers pertaining to the many issues surrounding marine and coastal GIS. Several methods of representation are discussed including polygon and raster-type models (Li, 2000; Raper, 2000). Dynamic segmentation, although not as complex as some models, has become one of the more widely used forms due to the ease with which it can be incorporated into current two-dimensional GIS environments (Li, 2000). Dynamic segmentation is implemented by dividing a linear coastline into unique segments based on differing attributes of coastal areas. The segments are defined in the GIS database by measurements from a selected starting point on the coastline, as opposed to geographical coordinates and the arc-node topology of the GIS. Bartlett *et al.* (1997), Sherin (2000), and Li (2000) discuss the many advantages of dynamically segmenting coastal data, including:

(1) Attributes are handled independently from the underlying arc-node topology (Bartlett *et al.*, 1997);

(2) Different levels of detail and resolution can be applied to the same set of attribute data (Li, 2000; Bartlett *et al.*, 1997);

(3) The linear structure is meaningful and easily recognizable as a coastal form (Bartlett *et al.*, 1997);

(4) Adjusting or adding new attribute information does not require any graphic manipulation, but simply a modification of distance values in the database tables (Sherin, 2000; Li, 2000);

(5) Both the quantity and complexity of storage, and the maintenance of geometric and topological information is reduced because the GIS is only required to store one copy of the line (Sherin, 2000);

(6) Attribute databases "can be combined and queried in an *ad hoc* manner, showing hidden relationships" in the data (Bartlett *et al.*, 1997);

(7) Greater flexibility in the data allows for "greater potential for modeling shoreline dynamics within the GIS (Bartlett *et al.*, 1997).

Practical applications of dynamic segmentation are rare in the current coastal GIS literature. Bartlett (1993), however, suggests that even though its potential has not yet been thoroughly tested, dynamic segmentation offers distinct possibilities for more effective coastal representation in GIS.

To date, most practical coastal GIS systems are based on the geomorphological segmentation of a linear coastal feature. This format provides basic representation of visibly distinct sections of coastline, which can be easily identified in the real-world. In the GIS, individual units of coastline are assigned unique ID numbers, which are subsequently linked to specific attribute values (Owens and Dewis, 1995; Harper *et al.*, 1991). Unlike dynamic segmentation, the segments are referenced using geographical coordinates and arc-node topology. Multiple map layers may exist, each representing different attributes of varying spatial extents. However, in large databases with numerous attributes, multiple map layers will increase processing time.

Most current coastal GIS applications examine coastal zone management issues such as erosion monitoring (Dimov, 2002), flood risk assessment (Thumerer *et al.*, 2000), or general evaluation and inventory (Andersen, 1997). These studies rarely discuss the problems associated with shoreline representation. The GIS is, more often, used as a database and mapping tool as opposed to a spatial analysis tool (Goodwin and Palerud, 1997; Laflamme *et al.*, 2001). In these cases, producing improved coastal models for the purpose of enhancing spatial analysis is not a high priority.

2.2.2 GIS and Oil Spill Response

Many tools and techniques for managing oil spill response operations rely heavily on paper documentation, which can greatly impede the timely implementation of response procedures and effective information flow (Ranger and Cassas, 1995). The cumbersome nature of paper documents impedes the ability of response personnel to quickly access information. Furthermore, paper atlases and documents require continuous updating, which is a time-consuming process that is not always performed frequently enough to maintain reliable information sources (Sorensen, 1995).

Advances in GIS storage, mapping and analysis tools offer a means of surmounting the inadequacies of traditional response management methods. A coastal

GIS can be rapidly and frequently updated, can provide almost immediate access to data, and can act as an analysis and modeling tool for evaluating oil spill events (Fedra and Feoli, 1998). The rapid response time and flexibility of a GIS help ensure the timely coordination of response proceedings, thereby potentially minimizing the effects of an oil spill (Sorensen, 1995). Green (1996) states that when implementing oil spill response proceedings:

> much hinges on the availability of up-to-date geographic or spatial information. More people are recognizing that obtaining the right information when we need it is vital if we are to prevent or at least minimize environmental damage to our coastlines from oil spills. As a result, an increasing number of GIS databases are being established for coastal areas.

These spatial databases contain the necessary data for devising oil spill response proceedings, and are quickly becoming an essential tool.

Laflamme *et al.* (2001) produced an extensive oil spill sensitivity database for Atlantic Canada. The system consists primarily of a large shoreline spatial database containing information on coastal characteristics, resources and response techniques. The database is linked to a segmented coastal map, such that each unique segment is assigned specific values for every attribute in the database.

Owens and Dewis (1995) developed a similar pre-spill database system that was based on a segmented coastal map presented as a GIS layer. The map was linked to the coastal databases, which contain information pertaining to shoreline characteristics and individualized response options for each unique section of coastline. Relevant information is output and presented in a relatively reader-friendly format, based on a predefined output template.

To date, most oil spill applications only use the GIS as a spatial database, or mapping tool (Ranger and Cassas, 1995; Galagan *et al.*, 1992), and do not exploit the full potential of GIS for spatial analysis purposes. This trend is partially due to the several short-comings exhibited by current GIS programs. Green (1996), among others (Ji and Johnston, 1995), points out the inadequacies of modeling inside a GIS. Environmental modeling can often become highly complicated and may be better handled by a separate modeling environment than by a GIS. Oil spill evaluation models such as GNOME or ADIOS, developed by NOAA, predict oil spill movement and behaviour based on a number of conditions. Many recent research efforts focus on integrating a separate modeling environment with the GIS, such that data can be transferred between the two systems (Galagan *et al.*, 1992; Smith and Loza, 1994; Ji and Johnston, 1995; Li *et al.*, 2000; Goto *et al.*, 2001).

A severe lack of oceanographic data still limits the extent to which oil spill modeling can be achieved, particularly in areas that have not been sufficiently surveyed (Green, 1996; Bartlett, 1999). In such cases, the use of a more simplistic model can be an effective means of analysis. Simplified models can be successfully established within the GIS to produce valuable information. Goodwin and Palerud (1997) implemented a basic oil spill trajectory model within a GIS, which was capable of identifying affected coastal areas.

2.3 Expert Systems

The origins of knowledge-based or expert systems can be traced back to the mid-1960s, during the early years of artificial intelligence research. Expert systems, considered one of the most important developments in artificial intelligence (Hoffmann, 1998), were established in the attempt to create computer systems with human-like intelligence. This objective was achieved by designing programs that used production rules based on the heuristic knowledge of experts to solve problems in a given domain (Durkin, 1994)

Openshaw and Openshaw (1997) discuss the use of expert systems, and list the numerous benefits presented by this technology, all of which are applicable to an oil spill response situation:

(1) They can make oil spill response expert knowledge and advice more accessible;

(2) Standardization of knowledge promotes a reduction in error; i.e. knowledge from multiple oil spill response sources are integrated such that conflicting views can be resolved, and there is a decreased chance of encountering judgment errors;

(3) They can help in the preservation of oil spill response expertise that will be preserved beyond the life span of any human expert;

(4) They simplify the management of an otherwise complex situation by organizing the numerous intricately connected rules, for example, relating to the types of response techniques that are applicable to various coastal environments;

(5) They establish a level of consistency in "complex decision-making by ensuring that the rules are consistently and objectively applied without emotion, prejudice or favor (Openshaw and Openshaw, 1997)", thereby providing a degree of objectivity throughout the oil spill response decision-making process;

(6) Automation of the decision-making process increases speed and efficiency, allowing for rapid response to an emergency oil spill situation;

(7) They are a means of commodifying an intangible resource (i.e. oil spill response knowledge) in a form that can be readily and widely distributed.

The main advantage of expert systems, however, is the ability to explain a line of reasoning and justify conclusions in a way that the user can easily comprehend (Openshaw and Openshaw, 1997). All output from an expert system is presented in a natural language format that is straightforward and familiar to the user (Acquired Intelligence, Inc., 2001).

Expert knowledge, within the expert system, is maintained as a knowledge base consisting of numerous rules. These rules, or production rules, represent expert reasoning using propositional logic, such that ***If A and B…Then C*** (Nikolopoulos, 1997; Durkin, 1994). The rules represent an expert's understanding and experience of a problem domain, and therefore do not require explicit mathematical relationships. The rule-based format offers much greater flexibility than traditional algorithm-based programs, and better represents the reasoning process of the human expert (Diamond and Wright, 1988).

The earliest practical expert system was developed for NASA as a tool to perform chemical analysis of "Martian" soil on an unmanned spacecraft (Buchanan and Feigenbaum, 1978). Since that time, the use of expert systems has expanded dramatically to include applications in numerous fields such as medicine (Buchanan and Shortliffe, 1985), land-use planning (Zhu *et al.*, 1996), ecology (Li *et al.*, 2002; Galbraith *et al*, 1998), and transportation (Spring and Hummer, 1995).

Development of an expert system typically involves four key phases (Kelly, 1991; Acquired Intelligence Inc., 2001):

(1) Determine the problem – Define the reason for constructing the expert system, and ensure that it is a feasible undertaking;

(2) Knowledge acquisition – Collect knowledge from expert sources, and determine the data and knowledge necessary for input into the expert system;

(3) Knowledge organization – Establish input and output variables and construct rules that combine this information, to further derive solutions to the proposed problem(s);

(4) Development of user reports – Compose "natural language" reports, which incorporate results from the expert system, and present them in a manner easily comprehensible to the user.

In reference to step one, not all problems are suited to the use of an expert system. In many cases, it is feasible to solve a problem through less intensive methods, such as a simple statistical analysis. In such cases, developing an expert system would be an unnecessary complication (Kelly, 1991).

Traditional oil spill response decision-making exhibits several characteristics that indicate that this type of situation is ideal for the application of an expert system. A heavy reliance on expert knowledge and advice is particularly demonstrative of the potential for expert system use. Oil spill experts possess an extensive understanding of oil spill behaviour, marine and coastal dynamics, and response procedures and techniques (Owens, 1995; CONCAWE, 1981). While many aspects of spill behaviour can be modeled numerically, identifying the appropriate response techniques to use in a given situation requires a more intuitive approach. Based on scientific analysis, logical reasoning, and prior experience, an oil spill expert will draw conclusions and develop a suitable plan of action. See Figure 2.1 for a simplified oil spill response decision-making process.

The availability, or lack of availability, of experienced oil spill experts offers additional justification for establishing an oil spill response expert system. An oil spill event necessitates almost immediate action, however contacting and informing an oil spill response expert can be time-consuming and difficult. Response experts are not continuously available, but unfortunately oil spills can occur anywhere, at any time (Green, 1996).

2.3.1 Action Tables

Action tables are a form of denoting rules that are used in the ACQUIRE® expert system software, and will be employed in this research (Acquired Intelligence Inc., 2001). Action tables are a type of decision table, and are an effective method of representing relatively complex logical relationships in an easily understandable format that can be processed efficiently (Hewett and Leuchner, 2003).

Action tables represent logic in a tabular format. The table or tables consists of "conditions" and "decisions", whereby a combination of conditions determines the outcome of the associated decision (Table 2.2) (Vanthienen and Wets, 1994; Acquired Intelligence Inc., 2001). The "condition stub" and the "decision stub" represent the names

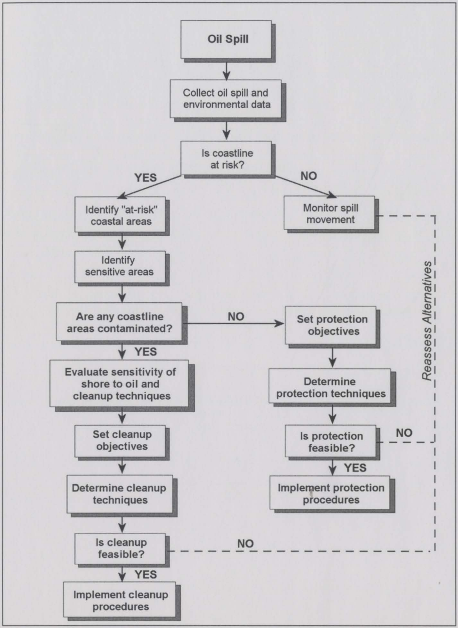

Figure 2.1: A flow chart depicting a simplified oil spill response decision process (modified from Breuel (1981)).

of the condition or decision variables being evaluated. The "condition action" and "decision action" describe the possible states of each stub. For example, if the condition stub is "coastline type" and the decision stub is "use exclusion booming", then the condition action may be "mudflat" and therefore the decision action would be "yes" or "no" (McDaniel, 1978; Acquired Intelligence Inc., 2001).

Table 2.2: Format of a decision table.

Condition Stub 1	Condition Stub 2	Decision Stub
Condition Action1	Condition Action 2	Decision Action

In ACQUIRE® the action table is divided in to "left-hand side" (LHS) and "right-hand side" (RHS) objects; where the LHS objects represents the conditions and the RHS object represents the decision. There can be any number of LHS objects, but only one RHS object. An expert system in ACQUIRE ® is made up of multiple action tables, which can be easily modified and updated to adapt to new or changing knowledge.

The action table format offers several advantages over production rules, which are traditionally used in expert systems:

(1) They reduce conflict in the knowledge-base. In an action table all columns are non-overlapping and each column refers to exactly one configuration of conclusions, therefore inconsistency between columns will not occur because the system detects such conditions;

(2) They simplify organization of the knowledge-base, and make it easier to visualize the knowledge structure;

(3) They offer more expressive power than production rules, by representing every possible condition, but in a simplified format with a cohesive structure (Acquired Intelligence Inc, 2001).

2.4 Expert Systems and GIS

Robinson and Frank (1987) identified four areas of expert system development relevant to geographic information system research: (1) map design, (2) feature extraction, (3) geographic database management, and (4) spatial decision support. Applications which integrate a GIS and an expert system generally conform to one of two formats. The first, and most common type of application, incorporates intelligence into a GIS to help the user understand and perform geographic information processing in relation to decision-making (Smith *et al.*, 1987; Usery *et al.*, 1988: Burrough, 1992; Openshaw, 1992; Openshaw and Openshaw, 1997). The second format links the GIS to an expert system, which contains domain-specific knowledge (i.e. knowledge about a problem separate from the GIS, such as medicine or environmental management) (Hammad *et al.*, 1993; Ferrier and Wadge, 1997; Faghri *et al.*, 2002).

The physical linkage between the expert system and the GIS can be developed using one of four common techniques (Fischer, 1994; Goodchild, 1992):

(1) Full integration – Expert system tools are integrated into GIS technology;

(2) Loose coupling – The two systems operate simultaneously and communicate with each other through an interface;

(3) Tight coupling – Either the expert system works around the GIS as a shell, or the GIS works as a shell around the expert system;

(4) System enhancement – Either the expert system is enhanced with spatial data handling capabilities, or the GIS is enhanced with rule-based systems capabilities.

The physical linkage between the GIS and the expert system allows data and knowledge to be communicated back and forth, significantly enhancing the functionality of both systems. This combination allows non-spatial information to be incorporated into the analysis of a spatially-specific problem (Canessa and Keller, 1997; Robinson and Frank, 1987).

2.5 Spatial Decision Support Systems (SDSS)

A Spatial Decision Support Systems (SDSS) is an integrated computer system designed to provide users with decision support for complex spatial problems. These systems enable the analysis of geographic information to be carried out in a flexible and user-friendly environment (Densham, 1991). SDSSs have been heralded as one of the most important and influential uses of GIS, a tool which itself has been renowned as a highly effective decision support technology (Canessa and Keller, 1997). A SDSS takes advantage of the many useful capabilities of a GIS, and combines them with additional decision support tools to create a single computer program, which serves to assist decision-makers (Densham, 1991).

In the past, and in some current cases, the GIS alone has often been labeled as a SDSS because of its proven ability to aid in locational decision-making. This view is disputed by most GIS and SDSS researchers (Armstrong *et al.*, 1990) due to certain shortcomings inherent in current GIS programs, particularly the level of expert skill required to effectively operate a GIS. Howlett and Bradstreet (1996) found that using a fully functional GIS package for oil spill response was often too complicated. Due to the high level of analytical power available, only a GIS expert could use the system effectively. A true SDSS must be user-friendly and provide useful and comprehensible output (Densham, 1990). In order to meet these criteria, supplementary programs, such as modeling environments or expert systems, are incorporated to provide additional functionality to the SDSS (Armstrong *et al.*, 1986; Armstrong and Densham, 1990; Zhu *et al.*, 1996). Additionally, a practical user-interface can promote easy access to data and analysis techniques in a fully-integrated system (Densham, 1990).

The architecture of the SDSS defines the layout of the above subsystems within the context of the full SDSS. The architecture can follow several possible formats. Sprague (1980) discusses a three-level framework for developing a SDSS, which defines the major structural features of a system. The three levels of technology in Sprague's framework include:

(1) SDSS Toolbox – hardware and software modules used to build a variety of system modules;

(2) SDSS Generator – mutually compatible hardware and software modules that can be configured to produce a specific SDSS;

(3) Specific SDSS – SDDS to solve a specific problem by combining some or all of the modules in the generator.

The architecture used by Armstrong *et al.* (1986, 1990) is based on the modular design proposed by Sprague (1980), and consists of five integrated software modules:

(1) database management system;

(2) model base management system;

(3) display generator;

(4) report generator;

(5) user interface.

The first four modules are encompassed by the user interface, which creates the appearance of a seamless system. Each module provides a specific group of capabilities, and information and data flows between the different groups.

Similarly, Armstrong and Densham (1990) suggest that the fundamental modules of a SDSS should include:

(1) a database management system;

(2) analysis routines;

(3) display and report generators;

(4) a user interface.

Armstrong and Densham (1990) suggest that a SDSS can be fully integrated by surrounding the above four modules by an expert system shell; possible variations on the format of a SDSS are presented by Densham (1991) and Zhu *et al*. (1996, 1998). In other cases a separate shell was developed around all of the modules creating a unifying user-interface, which is typical of loosely coupled systems (Fischer, 1994; Fedra, 1991).

Faghri *et al*. (2002) developed a SDSS for determining the location of park-and-ride facilities. This system integrated a GIS with an expert system in order to aid decision-makers with a location-allocation problem. Faghri *et al.* (2002) found the knowledge acquisition to be time-consuming, but the final SDSS was considered accurate, fast, user-friendly and robust.

Filis *et al.* (2003) produced a similar system for the purpose of identifying optimal locations for apiaries. This system incorporates a GIS, a relational database management system, and an expert system in order to assist beekeepers in determining optimal locations for bee colonies. The system allows beekeepers to examine spatial data concerning land cover, plant locations and meteorological conditions, which can then be accessed by the expert system through the relational database. The expert system evaluates the conditions, and identifies potential locations, which are added to a list of proposed sites. The system was found to be very efficient and user-friendly, particularly in terms of access to GIS data.

The SDSSs produced by Faghir *et al.* (2002) and Filis *et al.*(2003) are representative of the typical format of systems that are currently being implemented. More importantly, both of these systems also take full advantage of the analytical tools contained in the GIS. Recently, SDSSs have been produced in abundance, with applications in a variety of fields, particularly areas such as land-use planning (Diamond and Wright, 1988; Thomas, 2002), environmental management (Fedra, 1991, Zhu *et al.*, 1998; Thumerer *et al.*, 2000), and medicine (Robinson *et al.*, 2002). Although, many of these systems have proven effective in aiding decision-makers, several issues are obviously still problematic when implementing a new SDSS. Patterson (1999) identifies four major problem categories that should be addressed:

(1) Appropriate data resolution – The resolution must be suitable for any given analysis, and yet not be so cumbersome as to slow system processing;

(2) User feedback and interaction – The system must allow for feedback and interaction from the user in order to insert new knowledge and information;

(3) Extensions and customizations – The system must allow for changes and updates, so that it can grow according to the needs of decision-makers;

(4) Organizational issues – The system should account for the fact that different groups or organizations will have varying perspectives concerning the given problem.

Overall, a SDSS is considered successful if it is technically accurate, easy-to-use, and can verifiably assist decision-makers in solving a complex problem.

2.5.1 SDSS for Oil Spill Response

Few oil spill response SDSSs have been presented in recent literature. The systems that do exist often combine the GIS with a separate modeling environment for oil spill behaviour modeling (Galagan *et al.*, 1992; Smith and Loza, 1994; Ji and Johnston, 1995). Goodwin and Palerud (1997) produced a coastal SDSS that incorporated an oil spill model directly into the GIS. The completed system was considered effective for rapidly developing a contingency plan. However, one problem Goodwin and Palerud (1997) encountered was a necessity for the user to possess expert knowledge of the problem domain (i.e. oil spill response).

The use of an expert system as an additional module in the decision-making process would help overcome the problem encountered by Goodwin and Palerud (1997). Almost no current coastal management SDSSs incorporate expert systems, although several sources allude to the obvious necessity of expert knowledge when assessing oil spill and environmental management issues (Green, 1996; Goodwin and Palerud, 1997).

Upon inquiry, Canessa and Keller (1997) discovered that response personnel found a SDSS with only GIS and modeling capabilities was not completely adequate. One reason given for this conclusion was the inability of the GIS to evaluate non-spatial factors; a point that, again, reiterates the potential offered by an expert system.

Ji *et al*. (1992) have produced one of the few research papers describing a fully-integrated SDSS with an expert system to assess coastal issues. The expert system contributes the knowledge that is necessary to overcome the criticisms encountered by Canessa and Keller (1997). The expert system enables the SDSS to evaluate the non-spatial factors that are essential for producing realistic advice. In the event of an oil spill, a similar system would provide rapid and effective guidance to response personnel, thereby eliminating many time-consuming activities and improving the overall effectiveness of response operations.

CHAPTER 3

Study Area and Data

3.1 Location, Geomorphology, and Environmental Conditions

The study area for this research encompasses the greater part of Anaktalak Bay on the coast of Northern Labrador, Canada (Figure 3.1). The selected coastline extends outward from the Edward's Cove port facility, located at the inner most portion of the bay. The Edward's Cove port facility is a new development associated with the Voisey's Bay Mining Project, which will substantially increase traffic in the Anaktalak Bay area.

Anaktalak Bay is a large, east-west oriented fjord extending inward more than 50 km from Labrador's outer coastal area of the Labrador Sea. At its widest point, the bay measures more than 7 km[1] across, narrowing to approximately 1.2 km near the south-west coast of Satosoak Island. The study area will incorporate the areas of Inner Anaktalak Bay (ABI) and Outer Anaktalak Bay (ABO). A few small islands are located in the study area, adding an additional 31 km of coastline.

Much of Anaktalak Bay, including Edward's Cove, is made up of beach and estuary shore types. The total study area coastline measures 174 km in length, including 46 km of solid bedrock, 121 km of sand or gravel beaches, and 6 km of estuaries. Almost the entire extent of the shore is lined with natural boulder barricades, in addition to many

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[1] All distance and length values were calculated in ArcView from a 1:50 000 NTS digital mapsheet.

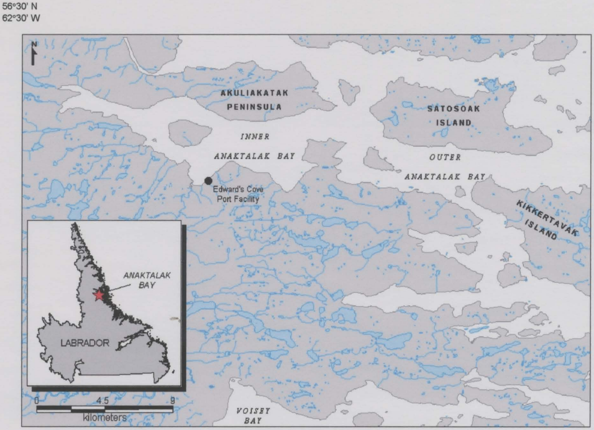

Figure 3.1: Study area selected for the Oil Spill Response Spatial Decision Support System including Inner Anaktalak Bay and Outer Anaktalak Bay, Labrador.

shallow water shoals, both of which can be problematic in the event of an oil spill (Jacques Whitford, 1997a).

Currents within the bay are considered weak, especially in the area of Edward's Cove, where they rarely exceed 0.036 km/hr (0.19 knots). However, even weak currents will transport surface oil rapidly enough to be problematic. The currents are greater towards the outer extents of the bay, increasing to 0.9 km/hr (0.5 knots) near Kikkertavak Island (Hatch Associates Ltd., 1997).

Wind direction and wind speed, which exhibit significant control over surface currents, are variable throughout the year. The winds within the bay trend westerly, with average speeds ranging from 10 to 17 km/hr (5.4 to 9.2 knots) (Green, 1997). The fjord characteristics of the bay force winds to blow along the east-west axis of the fjord. For example, a northwest wind over open water would shift to westerly within the fjord. Additionally, prevailing winds blowing along the fjord's axis can result in a funneling effect, producing strong, gusting winds, which can reach as high as 92.6 km/hr (50 knots) in the Anaktalak Bay area (Lancaster and Gray, 1993).

The flow of any oil released within the bay will be primarily controlled by a combination of ocean currents, and wind direction and speed. According to basic oil spill models, oil moves with the surface current and, additionally, moves at 3% of the wind speed (van Ooudenhoven *et al.*, 1983). Therefore, even with a current of only 0.036 km/hr, and a windspeed of 20 km/hr, an oil slick could easily spread over half a kilometer within one hour.

3.1.2 Significance of The Voisey's Bay Project

Until recently, Anaktalak Bay has remained pristine as a result of minimal anthropogenic impact. The discovery of substantial nickel deposits near Voisey's Bay, Labrador in September of 1993, has quickly altered these circumstances. In 1994 the Voisey's Bay Nickel Company (VBNC), a subsidiary of INCO, purchased the mineral claim and began steps to develop a mine and mill at the site. Now, with the Voisey's Bay Mining Project underway, Anaktalak Bay has become the key transportation route for materials and supplies being moved in and out of the Voisey's Bay region through the, soon to be completed, Edward's Cove port facility.

The Edward's Cove port facility, in Anaktalak Bay, is located only 8.5 kilometers north of the Voisey's Bay Mining Site. The port facility, at the innermost extent of Anaktalak Bay, requires shipping traffic to travel almost the full extent of the bay, therefore rendering most of the area susceptible to potential oil, or other contaminant, spills. Risk of oil spills in the area will increase due to the high levels of shipping traffic that will accompany mining developments. The VBNC is proposing to ship approximately 1,250,000 metric tons of nickel-copper-cobalt concentrate and 150,000 metric tons of copper concentrate annually. Additionally, at least 20 trips carrying 5000 metric tons of fuel would be required to deliver the annual fuel requirements during peak operations (Barbour *et al*, 1999).

Some precautions have been established to deal with the threat of oil spills in Anaktalak Bay. The Canadian Coast Guard (CCG) has approved a temporary oil handling facility currently in place at Edwards Cove. Vessels traveling to and from the port site are required to have a response plan prepared, known as the Shipboard Oil Pollution Emergency Plan (SOPEP), which must be certified by the CCG. Owners of ships must also have a contract with an approved response organization that would respond to major oil spill incidents. For the Anaktalak Bay region, this organization is the Eastern Canada Response Corporation (ECRC), based in St. John's, Newfoundland (Voisey's Bay Mine and Mill Environmental Assessment Panel, 1999).

3.2 Data

Spatial data for use in a GIS is often limited. Provided the required data does exist, it may still be expensive or difficult to obtain. If the data does not exist, collecting new data is an option; however, this process is both expensive and time-consuming (Green, 1996).

Both digital and hardcopy maps for much of Labrador are limited and difficult to acquire, including for the area of Anaktalak Bay (Figure 3.1). This area has only been surveyed in recent years due to the growing attention focused on Voisey's Bay. Most data available for this thesis were in the form of topographic mapsheets, which were available in digital form.

3.2.1 Topographic Data

The primary sources of GIS data for this research are based on 1:50 000 NTS (National Topographic System) digital mapsheets. The entire study area is encompassed by two map sheets, 14D/8 and 14C/5, which extend from 56° 15' N to 56° 30' N, and from 61° 30' W to 62° 30' W.

Coastal data for the study area was obtained from the results of a coastal survey conducted by Jacques Whitford Environment Ltd. for the Voisey's Bay Nickel Company in 1996. This survey collected information pertaining to the geomorphological, ecological, and anthropogenic attributes of the coastline. The data were referenced to a linear coastal model, which was divided into segments based on geomorphological units. The segments are based on visibly distinct geomorphological features as determined by a geomorphologist during the survey. Each segment is distinguished by a unique ID number, and all additional variables are defined based on the spatial extents of these units. The original data consists of two geographically-referenced databases, each linked to a segmented 1:50,000 digital coastal map by unique ID values. The original map data were provided in MapInfo (.tab) format, but were converted to shapefiles for use in ArcView (ESRI, 1997).

The original coastline dataset included the areas of Anaktalak Bay, Voisey's Bay, Kangeklualuk Bay, and the Outer Islands, all of which consisted of a total of 1274 coastal segments. However, because this data is being adapted for a prototype system, only a portion of the original coastline dataset was selected for use, in order to minimize complexity. The Anaktalak Bay area, consisting of 250 segments, was chosen for use in this research for two main reasons. First, this coastal environment exhibits great variety in its coastal attributes and therefore will be appropriate to thoroughly test the SDSS developed in this research. Second, Anaktalak Bay will soon be subject to an increase in shipping traffic and will be at higher risk for oil spills, therefore a functioning oil spill response support system will be beneficial to this area.

Additional 1:50,000 topographic data are used to provide supplementary topographic features to the system, including the land-water boundaries, water features, and contour lines. These data were originally in DXF format, which were processed in ARC/INFO to extract the required layers. The new layers were converted to shapefiles for further use in ArcView. All 1:50,000 data being used are provided in NAD 27 (North American Datum 1927) and are in vector format.

3.2.2 Ecological, Geomorphological, and Anthropogenic Data

Ecological, geomorphological, and anthropogenic data for the Anaktalak Bay coastline are linked to the segmented digital coastline maps discussed in the previous section. These data were collected by Jacques Whitford Environment Ltd. for the Voisey's Bay Nickel Company as a means of evaluating the susceptibility of the mapped coastal areas to oil spill damage, and therefore the data are representative of the type of information that is required for oil spill response decision-making.

The information was obtained primarily by aerial surveys of the coastline and visual identification of coastal characteristics. A video record of the flights was made, from which further information was gathered. Ecological and geomorphological characteristics were determined by experts from each of these fields. Anthropogenic attributes were determined from visual assessment and local knowledge.

The resulting data are contained in two databases. The first database pertains to general coastline characteristics, including qualitative measures of various floral species, presence or absence of human-use areas, presence or absence of various coastal characteristics, etc. The second database contains similar information for across-shore characteristics, and is subdivided into upper intertidal, lower intertidal, and supra-tidal zones. Combined, the original databases contained a total of 156 attribute variables (Table 3.1).

Table 3.1: A list of key variables contained in the oil spill response GIS database.

Shore Type	Wetland
Backshore Material	Fucus
Backshore Form	Mussel
Lower Intertidal Material	Barnacle
Lower Intertidal Form	Kelp
Exposure Level	Algae
Length	Urchins
Unit Width	Shoals
Unit Area	Strong Current
Trafficable	Boulder Barrier
Village	Sink
Camp	Tidal Pool
Shore Access	Estuary
Backshore Access	Channel
Oil Residence Index	Streams

3.2.3 Expert Knowledge[2]

Knowledge, for input into the oil spill response expert system, was collected entirely from written sources. The customary methods of knowledge acquisition fro expert system development are expert surveys and interviews, which involve direct interaction with the primary sources of knowledge. For this research, several of the

[2] Knowledge sources will be discussed here in the data section, however, it should be noted, that in this research knowledge and data are considered distinct and separate forms of information.

written sources, such as *Newfoundland Shoreline Mapping Northeast Coast/Burin Peninsula/Head of Fortune Bay* (Cormorant Ltd., 1997), were produced by experts, for personal use and for use by other experts. The information within these sources, therefore, is directly representative of expert knowledge and is highly detailed, particularly with regards to the selection of appropriate response techniques.

Knowledge acquisition is the most complicated, but also the most important step in establishing an expert system (Durkin, 1994). Often experts have difficulty verbalizing or organizing the required knowledge, which can frustrate attempts to explain the thought process that the expert system must emulate (Kelly, 1991). The benefit of dealing with oil spill response knowledge is that some degree of organization has already been attained. Oil spill response has become an absolute necessity in the past thirty years, and in order to deal with the rising demand for a quick and effective response, domain experts have been compelled to establish more structured planning tactics. The numerous written sources that exist on the subject are a substantial foundation from which to build a practical expert system.

The expert sources used for this research are specific to a Newfoundland and Labrador (Cormorant Ltd, 1997), and Atlantic (Owens, 1995) and Arctic environments (Owens *et al.*, 1998). The knowledge contained in these sources is appropriate for environments similar to Anaktalak Bay, which exhibit variable climate conditions, and a diversity of coastal formations and habitats. Knowledge and rules elicited from these sources generally coincide, and concentrate on similar types of response information.

For example, some of the most significant rules pertain to the relationship between the geomorphological formation of the shoreline and the appropriate protection or clean-up operations. As a specific illustration of this form of knowledge, CONCAWE's (1981) cleanup field guide states, in the event that an estuary environment is at risk, it is necessary to "reduce the inflow of oil by whatever means are available (booms, closing of tidal locks, etc.), and use the outgoing tide to support cleaning action."

Most sources are similar in form to the CONCAWE (1981) reference cited above, whereby the specific environments and environmental conditions help prescribe a course of action. These types of relationships are extracted from the texts and used to identify the numerous factors that are relevant to oil spill response decision-making. The factors involved will become the input and output variables for the expert system, while the linkages between them form the basis for specific rules within the knowledge-base.

Additional expert knowledge was collected from more general documentation, including reference manuals (Owens *et al.*, 1998), books (Breuel, 1981; Doerffer, 1992), and reports (Dempsey *et al.*, 1995). These sources were particularly important for the acquisition of explanatory data, which is used in the expert system to justify decision-making and clarify response options.

Two main types of explanation are included in the reports – explanation of reasoning, and explanation of strategies and techniques. Most of the oil spill response documents used in this research contain detailed descriptions of response routines and practices, including illustrations of equipment types and step-by-step procedures. Likewise, the reasons for recommending particular procedures are justified within the text. For example, in Owens *et al.* (1998) *Field Guide for Oil Spill Response in Arctic Waters*, it is recommended that mud flats be allowed to recover naturally *because* "treatment is usually difficult from an operations standpoint, and response activities may cause more ecological damage than the oil." In order to provide the user with a comprehensive account of the situation, it is essential to include this type of explanatory information in the user reports.

The primary source document used to obtain oil spill response knowledge for this research is a technical report prepared by a company specializing in oil spill response consultation (Cormorant Ltd., 1997). The document presents response knowledge for Newfoundland arranged as a collection of rules, whereby the specific conditions of an oil spill situation determine the appropriate actions to be taken. The rule-based format of the document is an effective means of organizing the knowledge. As a foundation for establishing an expert system, these rules provide the most fundamental knowledge for oil spill response.

CHAPTER 4

Methodology

Oil spill response decision-making is a complex task, which requires highly experienced experts who possess diverse and detailed knowledge in a variety of fields. The task of applying knowledge to such a complicated assortment of intricately connected variables can be overwhelming, particularly during an emergency situation. This research, through the development of a Spatial Decision Support System (SDSS), aims to reproduce this integration of knowledge and data, in an automated environment. This goal will be accomplished by combining several systems, each with unique capabilities, into a single seamless unit.

This chapter is comprised of a detailed discussion of the methodology used in the development of the oil spill response SDSS. The chapter is divided into three sections corresponding to the development process, beginning with the construction of the expert system. This phase is based on the use of an expert system shell, which provides a pre-defined, systematic structure for establishing an expert system. Within this shell, the required input, output, and transitional variables are identified, defined, and finally used to construct rules, which form the foundation of the automated decision-making process.

The second phase of the SDSS production process involves the organization of spatial data in the GIS, and the development and automation of GIS functions. The GIS environment is modified and a program is written within the GIS to automatically process all of necessary task,s including an oil spill trajectory model for identifying coastal areas in the path of the oil spill. The script will output information relevant to oil spill response decision-making. The output will be used as input for the expert system.

The final stage of SDSS development integrates the products of the first and second phases in order to produce a single, unified system. The link is accomplished using the Visual Basic programming platform, which is compatible with both the expert system shell and the GIS. A Visual Basic GUI is created to run as an executable program. The executable initializes the SDSS and activates the following processes:

(1) Prompt the user for input;

(2) Activate GIS for calculation and output of spatial data;

(3) Format GIS output and transfer data to the expert system, *via* Visual Basic;

(4) Activate expert system for processing of spatial data and additional user input;

(5) Present both expert system and GIS output to the user through the Visual Basic GUI.

4.1 Expert System Development

Expert systems are developed for one main purpose, to capture and represent non-numeric knowledge and reasoning processes that are not easily represented using traditional computing approaches or traditional software architecture. Oil spill response situations are adaptable to this type of approach due to the heuristic nature of the decision-making process. An oil spill expert relies heavily on accumulated knowledge and previous response experiences to develop a plan of action. This understanding and experience can be translated into logical rules that can then be organized and stored in an expert system for rapid and easy access.

The expert system developed for this research is designed to emulate the reasoning process of an oil spill response expert during a spill response situation. The expert system is constructed using the ACQUIRE® software package (Acquired Intelligence Inc, 2001), which was developed specifically to serve as a foundation for building expert systems. ACQUIRE® was selected to run the expert system for several reasons:

(1) It supports Action Tables, which offer numerous benefits over traditional production rules (see Section 2.4.1);

(2) It allows the user to create an expert system without the need for extensive programming that is required by most other expert system development software;

(3) It facilitates the incorporation of uncertainty by including qualitative reasoning methods in addition to numerical methods;

(4) It is compatible with Visual Basic, and includes an ACQUIRE® ActiveX control, which enhances interaction with Visual Basic.

4.1.1 Knowledge-Base Development

An expert system is composed of two fundamental parts – the inference engine and the knowledge-base. The inference engine is the active part of the system that processes input information from the knowledge-base. However, it is the knowledge-base that forms the core of the expert system, where all of the rules, insight, and knowledge are brought together in an organized structure to represent the expert thought process.

The oil spill response knowledge, for this research, is organized according to the structured format provided by the ACQUIRE® expert system shell. ACQUIRE® incorporates five main components into the knowledge-base development phase:

(1) Objects (Section 4.1.1.1);

(2) Rule and Object Network (Section 4.1.1.2);

(3) Rules (Action Tables) (Section 4.1.1.3);

(4) Cases (Section 4.1.1.4);

(5) User Reports (Section 4.1.1.5).

4.1.1.1 Objects

Objects are the fundamental building blocks of a knowledge-base, and are used to represent any of the variables that an expert takes into account when solving a problem. An object can represent something tangible, such as a measurement, action, or event, or something more obscure, such as an idea or hypothesis (Acquired Intelligence Inc., 2001). The oil spill response knowledge-base contains a total of 145 objects. For example, [Shore Type] and [Human Occupation] represent typical input variables that are objects, while [Natural Recovery] and [Exclusion Booming] represent types of decisions or conclusion variables that are also represented as objects.

Each object contained within the system is assigned a "value set" that defines the values associated with that specific variable. It is from these value sets that the user will select or input the specific attribute data to be used during the inference process.
A value set represents the attribute values of any type of data. For example, the variable [Human Occupation] is defined by the value set {"True", "False", "Unknown"}. The value "Unknown" is automatically incorporated into every value set; this option encourages explicit reasoning with uncertainty, which produces a more realistic decision-making environment (Acquired Intelligence Inc., 2001).

Value sets, and the configuration of ACQUIRE®'s inference engine, are based on symbolic input. Symbolic value sets, however, can not adequately describe certain variables, specifically those with non-predefined numeric values. In order to comply with the format of ACQUIRE®, numeric values must be translated into a symbolic form. This conversion is accomplished using "mappings", which allow a symbolic value to be associated with numeric values. For example, the [Oil Residence Index] (ORI) value set for the oil spill response knowledge-base describes oil residence in terms of duration (i.e. "Days to Weeks", "Weeks to Months", etc.). The ORI values being input into the expert system, however, are numeric, ranging from one to five. The value set mapping allows the system to accept these numeric values, and to determine the equivalent symbolic form. The ORI values are input as numeric values (ex. 4), and then converted to a symbolic value (ex. "Months to Years") which are then suitably formatted for processing by the inference engine.

4.1.1.2 Object Network

The object network is established after all of the objects in the knowledge-base have been defined. The network serves to delineate the relationships between the objects. In any decision-making process, the final conclusions are based on an evaluation of the relationships between variables; in other words, the influence certain variables exhibit upon other variables. For example, in the event that a sand flat shore type is affected by an oil spill, vacuum recovery is one of the recommended treatment techniques. Therefore, it can be said that the object [Shore Type] influences the object [Vacuum Recovery]. The actual context of the relationship between the two variable will be established when the rules are developed. The Object Network defines the structure upon which these rules will be built.

In the Object Network each individual object (i.e. Focus Object) can have both supporting and supported objects. As shown in Figure 4.1, the use of an exclusion booming technique is determined by shore type, the "presence" or "absence" of an estuary, and the "presence" or "absence" of a channel. Additionally, the need for exclusion booming helps determine the need for inshore support boats. This set of linkages depicts only a small section of the whole network, which, in its entirety, represents the structure of the complete decision-making process. Figure 4.2, illustrates the relationship between a small network of objects (Figure 4.1) and a larger section of the network. Figure 4.2 represents only a small section of the entire network, and therefore indicates the high level of interconnectivity that can be present in a knowledge-base, and is present in the oil spill response knowledge-base.

4.1.1.3 Rules (Action Tables)

Rules are one of the most important components of the knowledge-base, and form the foundation of the inference process. The rules define the specific relationships between objects, based on the values that are assigned to the objects at runtime. Objects that are connected through the network are likewise connected by specific rules using the same pattern presented in the network. Combinations of different linked object values result in different conclusions to the given problem.

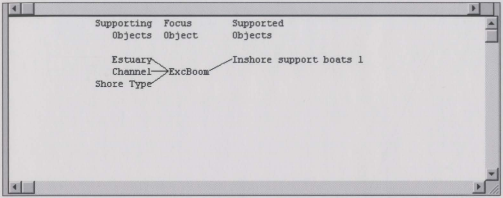

Figure 4.1: A section of the oil spill response object network within the object editor, representing the objects associated with the exclusion booming object.

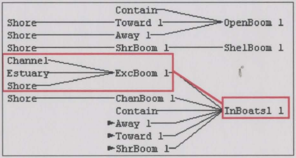

Figure 4.2: An expanded section of the oil spill response object network, indicating the position of Figure 4.1 within a larger context.

The ACQUIRE® system offers two options for developing rules, "action tables" and "production rules". Both rule formats can represent the same types of relationships between objects, and both conform to the production rule formula:

If A and B ... then C.

For example, in the oil spill response knowledge-base, a rule would follow the pattern:

> **If** a channel is not present **and** an estuary is present **and** the given coastal area is sand beach **then** exclusion booming is recommended;

or, as a production rule:

> **If** ([Channel] = [False]) **and** ([Estuary] = [True]) **and** ([Shore Type] = [Sand Beach]) **then** ([Exclusion Booming] = [Recommended]).

An action table can represent the same information as the production rule, but unlike the production rule, an action table accounts for all possible relationships between the values of the linked objects (Figure 4.3). Therefore, an action table is essentially a collection of many production rules. In Figure 4.3, the action table illustrates the relationship between [Channel], [Estuaries], [Shore Type] and [Exclusion Booming]. The specifics of the relations are further defined within in the table by 72 distinct rules. In ACQUIRE®, it is possible for a single action table to contain up to 10 000 rows or rules.

The contents of a full action table are considered a single rule in the knowledge-base, but the extensive contents of an action table are only accessed in the event that the initial rule is fired. In Figures 4.1 and 4.3, the initial rule is fired when the values of the objects [Channel], [Estuary], and [Shore] have all been set (i.e. they have all been

Channel	Estuary	Shore	RH Side
False	True	Boulder-Beach	Recommended
False	True	Pebble-Cobble-Beach	Recommended
False	True	Sand-Beach	Recommended
False	True	Sand-Flat	Recommended
False	True	Mud-Flat	Recommended
False	True	UNKNOWN	Recommended
False	False	Bedrock	Not-Recommended
False	False	Man-Made-Solid	Optional
False	False	Boulder-Beach	Not-Recommended
False	False	Pebble-Cobble-Beach	Not-Recommended
False	False	Sand-Beach	Not-Recommended
False	False	Sand-Flat	Optional
False	False	Mud-Flat	Optional
False	False	UNKNOWN	UNKNOWN

Figure 4.3: A section of the action table, from the oil spill response knowledge-base, depicting the rules for Exclusion Booming (RH Side).

assigned values). In the action table, these objects are referred to as Left Hand Side (LHS) objects, while the object that is being evaluated is the Right Hand Side (RHS) object. The value of the RHS object is set based on the conditions of the combined LHS objects.

The oil spill response knowledge-base contains a total of 62 action tables, each of which contains multiple rules. The LHS objects for this knowledge-base, as defined by both the object network and the action tables, represent known or observable conditions at the time of the spill, while the RHS objects represent potential solutions to the problem, in terms of recommended objectives, strategies, techniques and equipment.

In Figure 4.3, the RHS object represents exclusion booming. The value set for this object consists of four possible values {"Recommended", "Optional", "Not-Recommended", "Unknown"}that describe the relevance of exclusion booming under specific circumstances. For example, during an oil spill situation, if an estuary is present in the vicinity of a sand beach, but there are no river channels present, then exclusion booming is a recommended protection option. In the context of the full expert system, exclusion booming is one of many possible solutions, of which multiple solutions can be selected.

4.1.1.4 Case Setup

Once the action tables and rules for the expert system are fully established, the systems input values must be specifically characterized. The case setup is used to indicate which objects receive input, what type of input they receive, and from where that information is received.

A "case" is a collection of input values, which represents a particular situation or set of conditions to be evaluated by the expert system. Cases may be used to preset the values for objects in the knowledge-base. For example, the value of [Channel] can be set to "False" in the case. This value will be retained when the expert system is run, so that for all rules with [Channel] as a condition (LHS object), the value will be set to "False". In the oil spill response expert system all object values are described as "unset"; this implies that the objects have no set value prior to running the inference engine, and therefore must obtain input values from an outside source.

The source of input is defined through the case setup, which indicates whether values will be entered from either the preset case or from the user through the computer keyboard. Additionally, the type of input data is defined as either numeric, symbolic or both, which places limitations on the type data that can be input. For example, values for the object Oil Residence Index (ORI) can be represented as either a numeric (ranging from 1 to 5) or a symbolic (ex. days, months, years) value, however, in the expert system this object is identified as numeric, therefore input values for this object must be numeric.

The oil spill response expert system, as defined by this system's case setup, receives all data from a predefined case. As discussed above, all values in the predefined case for this system are described as "unset", but without specific values for the objects, the rules cannot be fired; therefore, the case values must be set at runtime. This task cannot be accomplished by using the expert system shell alone. The expert system needs to be controlled by an external program, which alters the context of the case at runtime. This operation is carried out using ACQUIRE®'s software development kit, which includes a Visual Basic ActiveX control and Library (.lib) file to facilitate programming the expert system. All functions of the expert system are controlled using Visual Basic, so that the expert system shell is never visible to the user (see Section 4.4 for full discussion). For example, the value for the object [Oil Residence Index] (ORI) in the expert system is supplied to the expert system through the Visual Basic code:

```
KBase.Acquire1.ObjectName = "ORI"
KBase.Acquire1.ObjectNumber = ObjVal.Item(42)
```

This section of Visual Basic code resets the value for ORI within the expert system case, changing it from "unset" to a number value, which is contained in position 42 of the referenced list (ObjVal).

4.1.1.5 User Reports

User reports are the main source of output for the ACQUIRE® expert system, and are used to present the conclusion values in a "natural language" format that can be easily understood by the user. Based on the potential output values produced by the inference engine, user reports are created to discuss and explain what the output means in terms of how specific conclusions were reached, what these conclusions mean and how to apply this newly produced information to the given problem.

The procedure for creating user reports is similar to the procedure for developing production rules, and is based on propositional logic. Conditions are established by applying the ***if...then*** rule format to the expert systems conclusion objects. If the conditions of a rule are met, then the section of text associated with the given rule is output as part of the user report. For example, in Figure 4.4, *If* the output object [Natural Recovery] is set to "Recommended" *then* a description of the Natural Recovery technique will be included in the report. Similar rules are established for all required output objects and values to conditionally include or exclude portions of the user report (Acquired Intelligence Inc., 2001).

```
RECOMMENDED SHORELINE TREATMENT OPTIONS:
<LINE BREAK>
(ie. the best treatment options for dealing with a shoreline segment that has come into contact with the oil slick)
<LINE BREAK>
<LINE BREAK>
<BEGIN CONTEXT: 98 (Natural Recovery = Recommended)>
   - Natural Recovery
   <PARAGRAPH BREAK>
   Natural Recovery means allowing the oil to recover naturally, and should always be considered the preferred option.
   <PARAGRAPH BREAK>
   It is generally necessary to monitor the location to ensure that the assessment is correct or that conditions do not change.
   <PARAGRAPH BREAK>
   This technique is implemented when:
   <PARAGRAPH BREAK>
   (a) the cleaning options have the potential to cause more damage than they prevent,
   <PARAGRAPH BREAK>
   (b) response techniques will not accelerate natural recovery or,
   <PARAGRAPH BREAK>
   (c) response operations could place cleanup personnel in danger.
   <LINE BREAK>
   <LINE BREAK>
<END CONTEXT: 98>
```

Figure 4.4: Structure of the *Shoreline Treatment* user report within the context of the ACQUIRE® expert system shell.

Five different user reports were created for the oil spill response expert system. Several output possibilities were produced in order to provide the user with options regarding the amount of detail they wish to view. The user can request a basic report containing only essential information, or can browse more comprehensive reports. Contents of the user reports are as follows:

(1) *Summary* – provides the initial information relevant to spill response for the given situation, including identified coastal areas at risk, resources at risk, and required equipment;

(2) *General Information* – provides the specific details of the oil spill including oil type and characteristics, environmental conditions and spill trajectory;

(3) *Shoreline Protection* – describes objectives, strategies, techniques and equipment required when coastal areas are at risk and must be *protected*;

(4) *Shoreline Treatment* – describes objectives, strategies, techniques and equipment required when coastal areas have been affected by the oil slick and must be *treated*;

(5) *Constraints* – describes the potential constraints, such as difficulties accessing the shoreline that could become problematic during oil spill response operations.

The user reports contained in the oil spill response expert system are automatically output once the inference engine has completed processing. However, as with the expert system case, the reports are manipulated using an outside program. Access to the five different reports is controlled by the Visual Basic application, which allows the user to select the desired report type or to alternate between reports (see Section 4.4 for full details). Additional information and images are also associated with the user reports through Visual Basic, based on the specific contents of each report.

4.1.1.6 Representing Uncertainty in ACQUIRE®

It is the hallmark of a proficient domain expert to be able to deal with any uncertainties that arise during a decision-making situation. In circumstances where only limited information or knowledge is available, experts should be able to draw upon previous experience and intuition to derive a solution. An expert system, therefore, should also be able to account for uncertainty.

Many of the traditional approaches to uncertainty in expert systems rely on *quantitative* methods, which represent levels of uncertainty in a numerical form and quantify conclusions using numbers such as confidence intervals and certainty values (Nickolopoulos, 1997). The ACQUIRE® system, however, uses a *qualitative* approach, based on the concept that highly skilled knowledge arises from pattern recognition and therefore "it is possible to implicitly resolve uncertainty in structuring the patterns. Therefore, there is no need to use additional numerical methods (Acquired Intelligence Inc., 2001)." Through the use of action tables, ACQUIRE® resolves uncertainty by explicitly assigning conclusion values (i.e. RHS values) to all patterns in the table. Any overlapping results are solved using preferences and biases, whereby preference is assigned to a particular pattern-consequence, or a bias is set towards selecting a particular kind of consequence. This method of characterizing uncertainty is more comparable to a human expert's approach to dealing with uncertainty, which is highly qualitative (Acquired Intelligence Inc., 2001).

The issue of uncertainty does not directly arise in the oil spill response expert system. All consequence values have been explicitly set in the knowledge-base without any overlap or conflicting output. However, this does not imply that the information contained in the expert system is not uncertain, just that action was taken to minimize uncertainty. Domain knowledge in general is still implicitly uncertain. Bonissone and Tong (1985) list four main sources of uncertainty in expert systems:

(1) Reliability of the information – resulting from ill-defined concepts in the observations, inaccuracy by instruments used to make observations, or weak implications in the systems rule sets;

(2) Inherent imprecision of the rule representation language – "if rules are not expressed in a formal language, their meaning cannot be interpreted exactly";

(3) Incomplete information – when required input information is unknown;

(4) Aggregation of rules from multiple knowledge sources – can result in conflicting, redundant, subsumed, or missing rules.

Although the first source of error is always difficult to avoid, even for human experts, ACQUIRE® does attempt to overcome the remaining three potential error sources.

The use of symbolic object values helps eliminate the second source of error by allowing values to be more representative of natural language or approximate reasoning. Values do not have to be discrete, they can be generalized using terms such as "somewhat" or "almost". For example, the oil spill response expert system, when evaluating the coverage levels of floral resources uses the values "none observed", "patchy", "occasional" and "continuous". These terms are more representative of the subjective evaluations of the user. ACQUIRE®'s action tables are developed to handle qualitative input and can provide consequence values for all combinations of input.

The third source of error is handled in ACQUIRE® by adding an "Unknown" value to all object value sets. If an objects value is "Unknown", the value is *not* unset and the system will still process all associated rules. The action tables account for the possibility of "Unknown" LHS values, and provide concluding outputs for such conditions. In some cases, the output will likewise be set to "Unknown", however, in other cases, viable conclusions are still possible. For example, when evaluating the concluding object [Contain Stranded Oil at Shoreline], two input variables are considered, [Prevent Alongshore Drift] and [ShoreType]. However, if ([Prevent Alongshore Drift] = "Unknown") and ([ShoreType] = "Mud Flat"), then the output value for [Contain Stranded Oil at Shoreline] is still set to "No" because it is never advisable to contain oil on a mudflat shore line due to the high potential for irreversible damages.

The fourth source of error is reduced in ACQUIRE® through the use of action tables. As discussed above (see Section 4.2.3.3*)*, action tables can reduce or even eliminate conflicting, redundant and missing rules. Action tables provide explicit conclusions for each set of conditions, therefore eliminating overlap. Filling the contents of an action table also ensures that no conditions are omitted. Any missing or redundant data is visible in the action tables and can be easily detected and edited.

4.2 Geographic Information System (GIS) Development

The coastal GIS implemented for this research contains highly specific data for the Anaktalak Bay coastline. The coastline is represented as a linear feature divided into segments representing geomorphologically distinct sections of coastline. Ecological, geomorphological and anthropogenic data are associated with the individual coastal segments through the associated database. The geographically referenced environment provided by the GIS allows this data to be analyzed in terms of relationships to the location of an oil spill event. Using a distance function in the GIS identifies attributes within a given distance of a selected map feature, such as an oil spill. The GIS also functions as an environmental modeling system to determine the trajectory of an oil spill and to identify coastal areas at risk of being affected by the spill.

The GIS is developed in three phases:

(1) Data preparation – Input and organize data pertinent to the expert system. This step includes organization of segmented coastal data;

(2) Analysis – Identify and implement the spatial analysis operations required to extract relevant data. This step will include formulating an oil spill trajectory model;

(3) Automation – Compose a script (i.e. Avenue program[3]) to run all components of the GIS including prompting the user for input, performing analysis procedures, and generating output for further use in the SDSS.

4.2.1 Coastal Data Representation and Preparation

The implementation of a GIS to handle oil spill response data introduces a new problem – the representation of coastline data in a GIS. Current GIS environments are formatted to deal primarily with land-based data (Ji and Johnston, 1995). Although the coastline is structurally and visually a part of the land, it is a very distinct feature with a unique form and function (Bartlett, 1999). Therefore, in order to effectively model the

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[3] Avenue is the object-oriented programming language specific to ArcView and used for controlling functions of the GIS.

coastline, the data should be modified to capture the characteristics of the coastline that make it a unique feature. Specifically, the model should represent the highly-dynamic nature of the coast, the multitude of variables associated with the coast, and finally depict the coast in a recognizable format.

The original GIS data for Anaktalak Bay were compiled from 1:50 000 NTS digital map sheets (see Section 3.2). The data are in arc-node format, the standard vector data format for current GIS programs, whereby each arc is defined by start and end nodes, represented by X and Y coordinates. For these data, the divisions of the segments conform to the geomorphology or exposure level of the coastline. The segments were identified by a geomorphologist based on visibly distinct units of coastline. All other attribute values adhere to these predefined segments. The full study area, including 12 offshore islands, is comprised of a total of 250 segments.

Dynamic segmentation was the initially intended structure for the Anaktalak Bay database. However, during the development of the SDSS it was determined that using dynamic segmentation to identify coastal areas based on measured distances is not necessarily a practical approach to coastal zone oil spill response. Oil spill response management is a complex operation that must proceed quickly. Based on these requirements, it was concluded that oil spill response operations would benefit more greatly from a basic linear model, which can be easily interpreted by users. Measured distances along a coastline may cause confusion during an emergency situation. Conversely, geomorphologically distinct segments, represented in a linear model, are easily visible, and can be quickly identified by response personnel to promote the rapid implementation of protection and cleanup operations.

The original coastal segment boundaries were maintained for use in the oil spill response SDSS. In order to reduce complexity, the databases included with the original data set were slightly modified. Initially there were two main databases associated with the Anaktalak Bay coastline, the general database and the across-shore database. In SDSS, the two data sets were joined to form one database, which was associated with the coastal linear segmented map. Multiple databases could easily be maintained and referenced inside a SDSS; however, in this case, both tables referred to the same segments, and therefore it is more efficient to store the information in a single database. The segments of the final database were assigned new unique ID numbers, from 1 to 250 in order to improve distinction and querying capabilities.

4.2.2 Spatial Analysis – Oil Spill Model

In addition to acting as a spatial database, one of the main purposes of the GIS within the oil spill response SDSS is to identify, through spatial analysis functions, the coastal areas that will be affected by an oil spill. A simplified oil spill model is implemented within the GIS to determine the trajectory and spread of an oil slick. Trajectory predictions for the model are based on basic vector calculations as described by Breuel (1981) and van Oudenhoven (1983). Owens *et al.* (1998) suggest that this form of simple analysis, which takes into account the speed and direction of the wind and current, "may be all that is required for an estimate of the movement of oil on water."

Oil on water spreads primarily as a result of wind and current movements. Oil on the surface will be transported at the same speed as water currents and additionally at 3 % of the wind speed. The direction of oil slick movement is based on the resultant vector of wind and ocean current directions and speed (Breuel, 1981) (Figure 4.5). The precise values can be calculated using triangle geometry. If the length (speed) and bearing of the wind and ocean current vectors are known, then the length (speed) of the oil slick vector can be calculated using the Pythagorean Theorem, such that $V_c^2 + V_w^2 = V_o^2$, where V_c is the ocean current velocity, V_w is the wind velocity, and V_o is the oil slick velocity. Subsequently, the bearing of the oil slick movement can be calculated based on the Law of Cosines, whereby angle measurements are determined by the lengths of the three sides of the triangle formed by the velocity vectors (Figure 4.5).

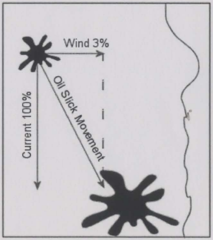


Figure 4.5: Vector model for determining oil spill trajectory.

Oil slick spread is calculated based on an ellipsoid model determined by Lehr *et al.* (1984) which is a modification of Fay's (1971) spreading model (Fallah-Araghi, 1975). The spreading of the oil slick as derived by Lehr *et al.* (1984) is a result of several factors, which cause the slick to form as an ellipse as determined by the equations:

$$\mathbf{b} = 1.7\,[(\rho - \rho_o)/\rho_o)]^{1/3}\,V^{1/3}\,t^{1/4};$$

$$\mathbf{a} = \mathbf{b} + 0.03\,U^{4/3}\,t^{3/4};$$

where **a** is the length of the major axis; **b** is the length of the minor axis; ρ is the water density (kg/m^3); ρ_o is the oil density (kg/m^3); V is the volume of spilled oil in barrels; t is the time in minutes; and U is the wind speed in Knots. The thickest section of the slick forms the ellipse, which is elongated in the direction of the wind current (Figure 4.6). The drifting movement of the oil slick ellipse is controlled by the wind and surface currents, which cause the thick section of the oil slick to drift along the spill trajectory, leaving a thinner slick in its trail.

The ellipse model, as developed by Lehr *et al.* (1984), is designed to estimate the total surface area of the ellipse, including both the thick and thin areas of oil, based on the major and minor axis of a calculated ellipse, such that:

$$A = (\pi/4)\,ab;$$

where A equals the area of the elliptical slick. The original spatial extent of the ellipse calculated by the model represents only the thickest portion of the slick, and does not include the thinner layer of oil surrounding this core. Therefore, as a modification, the

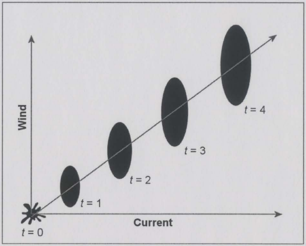


Figure 4.6: Oil slick spreading model (modified from Lehr *et al.*, 1984); t = time in hours.

major and minor axis were recalculated to reflect the actual area of the ellipse, based on the ratio of major to minor axis in proportion to the actual total area of the ellipse.

Using this model, hourly spread and movement of the spill can be mapped, and used to identify the extent of oil slick influence in relation to the coastline. In the GIS, a new map layer is created in which a series of ellipses represent the hourly spreading rate of the spill (Figure 4.7). A second, single polygon layer, is created which covers the full extent of the calculated oil slick for a given time period, as defined by the user. At-risk coastline segments are identified using a distance function of the GIS, which allows objects to be selected that are within a specified distance of another map feature. Initially, only those areas which intersect the calculated oil slick layer and will be inundated within in the allotted time period are selected. A second group of segments are

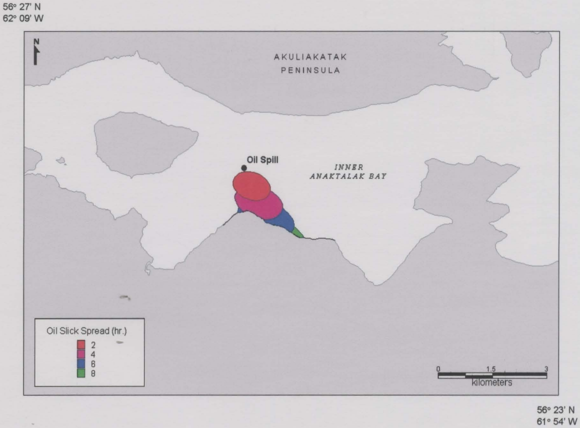


Figure 4.7: Sample spill calculated using the modified oil spill spreading model; V = 500 barrels, U = 2 Knots, ρ = 1000 kg/m$_3$, ρ_o = 840 kg/m$_3$.

selected to ensure that all potentially threatened coastal areas, which fall within 200 m of the modeled spill extent, are identified.

All selected segments are exported to a new map layer, which contains only those coastal segments that are affected or at risk of being affected. In this new layer the first and second set of segments, as described above, are distinguished from each other based on values added to the associated database. More specific data will also be attached to the new at-risk segment layer with regards to average distance from the spill source and estimated time to contact with the oil slick, both of which are calculated using the basic function of the GIS.

4.2.3 GIS Automation

In order to comply with the fundamental requirements of an effective SDSS, the functions of the GIS must be user-friendly (Densham, 1991). However, GIS software is too complicated to allow inexperienced users to perform effective analysis. In order to enhance user-control without jeopardizing the accuracy of the analysis process, the GIS must be managed, to some extent, by a source other than the user. By modifying and automating components of the GIS, the user can interact with the analysis process, but is not required to perform or make decisions about complicated analysis procedures.

All functions inside the ArcView system can be controlled through the program's own object-oriented programming language, Avenue. Any analysis functions that a GIS expert might utilize in a given situation can be run automatically using prewritten scripts. A single script can collect input from a user, access data, perform analysis, and produce output.

For the Anaktalak Bay SDSS, the main purpose of the GIS is to identify coastal areas at risk, access and output the data attached to these coastal areas, and produce visual hardcopy output depicting the affected areas. This complete process is accomplished by a single script (SDSS.ave), which is executed when the Anaktalak Bay ArcView project (Abgis.apr) is accessed. The script contains specific references to the Anaktalak Bay digital map layers in the GIS and associated tables. Functions carried out by the SDSS.ave script are as follows:

(1) obtain the location of the oil spill from the user;

(2) request wind and ocean current data from the user;

(3) predict the trajectory and spread of the oil slick (oil spill model);

(4) identify coastal areas, and associated attributes, in the path of the spill;

(5) create map layers for exhibiting the trajectory and spread of the spill, and the areas at risk;

(6) output text files containing specific coastline attribute data (for expert system input);

(7) create hardcopy maps, in JPEG format, indicating the trajectory and spread of the spill, and the areas at risk.

All operations within the GIS, therefore, are carried out automatically. During this stage of SDSS use, only minimal input will be required from the user. The complexities of spatial analysis and the GIS functions are transparent to the user. The ArcView graphical user interface (GUI) is also modified, to eliminate buttons, menus and extra tools that are not relevant to the functioning of the SDSS.

The final outputs produced by the GIS script include JPEG maps depicting the affected segments of coastline and a series of text files containing the required data for each affected coastal segment.

4.3 SDSS Development – System Integration and Structure

Both ArcView and the ACQUIRE® expert system shells are equipped with components that allow them to be managed by a developer. ArcView can be accessed and controlled, to a certain extent, by external programming, such as Visual Basic, in addition to its own programming language, Avenue. The content of ACQUIRE® can also be managed by a developer. This software comes equipped with a Visual Basic ActiveX control, which allows most of the functions of ACQUIRE® to be accessed directly through Visual Basic.

Integration of these two problem-solving programs, the expert system and the GIS, is accomplished using a loose coupling method. Loose coupling involves developing an interface that enables multiple systems to operate simultaneously and exchange information (Fischer, 1994). The GUI for the oil spill response SDSS is a Visual Basic application, which acts as a communication node between the GIS and the expert system (Figure 4.8).

The GUI (Figure 4.9) was designed to be both visually and functionally simplistic. The format of the system provides the user with constant guidance, and the user is never required to perform complicated tasks. Any components that require user

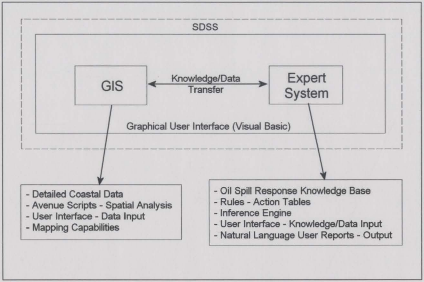


Figure 4.8: SDSS Architecture

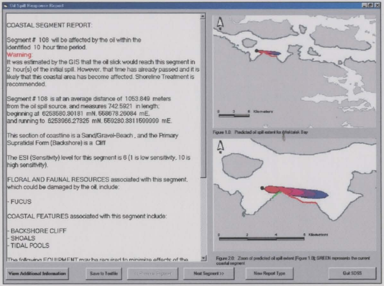


Figure 4.9: Main section of the SDSS's graphical user interface (GUI), used for viewing output information.

interaction are straightforward; either specific instruction is provided or required actions are made obvious by limiting input and menu options.

The interface also controls data access and processing. Upon initiating the system, the user is prompted for specific information concerning the oil spill, which is then used for further analysis in both the GIS and the expert system. This information is collected through the GUI, which then converts the necessary data to a text file format, which can be read and processed by the GIS. Once the appropriate information is entered through the Visual Basic interface and formatted for further processing, the decision-making operations begin. ArcView is accessed using a Dynamic Data Exchange (DDE) conversation, which opens the Anaktalak Bay project file (abgis.apr). This action then initiates the SDSS.ave script inside the GIS, which runs the initial spatial analysis of the identified oil spill (see Section 4.3.2).

Once the functions of the GIS script have completed, control of the system is passed back to the Visual Basic application, which accesses the output data and associated JPEG maps produced by the GIS analysis process. At this stage of the processing, the Visual Basic application reads each output data text file separately, and then transfers the content of each text file to the oil spill response expert system in the form of a case (see Section 4.1.1.4). The format of the case is predefined by the expert system in terms of what variables can be entered and whether these variables are numeric or symbolic.

When the input values have been passed successfully to the expert system, then the Visual Basic GUI implements the expert system's inference engine to evaluate the first case. The inference engine is the functional component of the expert system, which manages the knowledge-base and input data to solve the defined problem. The main results produced by the inference engine are values for the consequence variables (i.e. results or RHS values) in the knowledge-base, which are then translated into a natural language format through the user reports.

The user is prompted to select the initial user report from a predefined list in the form of a drop-down menu provided by the GUI (Figure 4.10). This action opens the main viewing window of the SDSS, which displays the selected report type for the first coastal area and the associated map JPEGs (Figure 4.9). Reports for the remaining coastal areas are accessed using the *Next* and *Previous* buttons to cycle through each set of associated user reports and JPEGs. These buttons prompt the application to read each GIS data text file sequentially and reset the expert system case for each file. After resetting the case, the inference engine is reactivated, user reports are produced pertaining to each coastal segment, and the resultant reports are displayed for the user.

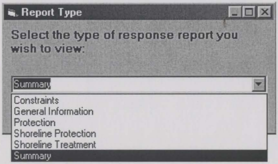


Figure 4.10: Drop-down menu used to select and view different oil spill response reports.

The user report type can be changed at anytime during an information viewing session by selecting the *New Report Type* button. This button resets the expert system case to the first GIS text file, and reinitiates the process of cycling through the user reports for each coastal area as guided by the user.

Additional information related to the context of the current user report is provided through the *View Additional Information* button. As each user report is read into the Visual Basic rich textbox, the text is scanned for relevant keywords or key phrases, for example "Natural Recovery" is a common key phrase. If a word or phrase is identified in the text, it is highlighted, and any related topics are added to a list. If the user requests additional information, a drop-down menu, containing the compiled list of highlighted topics is displayed. Selecting a topic will provide the user with information on the given topic in the form of a JPEG containing relevant text and images (Figure 4.11). The additional information is provided as a means of conveying details about oil spill response that are not necessarily crucial, and therefore are not contained in the user reports, but may still be helpful for further explaining the situation to the user.

As a final option, the user can save each of the user reports as individual text files. The *Save to Text file* button activates a *Save As* dialog box, which allows the user to save the text file under any provided name, or as the default name, which is individually numbered for each GIS file in the format *Segment<file#>.txt* (e.g. Segment1.txt). Once the user reports for all coastal segments (or files) have been viewed for a selected report type, the user is informed that all segments have been processed. The user is then offered the choice of either selecting a new report type or quitting the SDSS. Selecting a new report type will, again, reset the expert system case to the first file and recommence the cycle of presenting reports for each coastal segment. Choosing to quit the SDSS will completely reset the system, and close the SDSS.

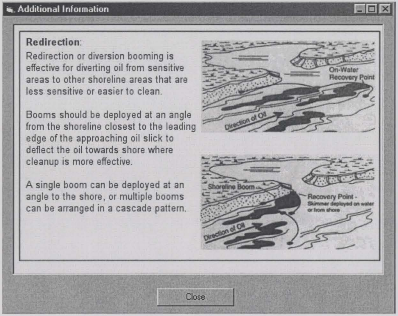


Figure 4.11: Example of *additional information* regarding redirection techniques provided in the SDSS.

4.3.1 Error Traps

In order to ensure that the SDSS functions efficiently and is capable of handling incorrect user input, error traps were created within the programming of both the GIS and the Visual Basic application. These error traps were included as a means of controlling user input, and therefore preventing the system from failing as a result of invalid data entry.

For example, in the event that the user enters an oil spill coordinate that does not fall within the appropriate water boundary, the system will inform the user that the values are not valid, and prompt the user to re-enter the information. This error trap makes use of the spatial querying functions within the GIS, whereby features of a GIS layer can be selected based upon the extents of another layer. Therefore, using the land boundary GIS layer, the oil spill point layer can be queried. If the oil spill is not located within the land boundary then it is located in the water, and therefore is a valid point. Also, a second query is used, whereby the GIS determines if the oil spill point is located within a specific geographical extent that represent the boundaries of the study area for the SDSS. When the SDSS receives a valid oil spill location, then the system will continue processing.

Additional error traps include the use of drop-down menus, which limit and control the input of the user. Drop-down menus help prevent any erroneous data from being entered, and therefore, will also help avoid a system failure. Any other data values that must be entered by the user, without the use of a drop-down menu, are checked against a range of valid values for that specific type of data. If the value is determined to be invalid, then the user is notified, and is prompted for new input.

In order to identify error sources, the SDSS was run numerous times using deliberately invalid input. Points at which the system failed, or accepted invalid data were noted, and the code for both the GIS and the Visual Basic application were modified to account for these potential errors.

4.4 Summary

The prototype SDSS, as developed by the above methodology, unifies multiple sub-systems to form a single, powerful decision making tool. The development process was completed in three stages: (1) building the expert system, (2) adapting the GIS and (3) integrating the systems to create the SDSS. The Visual Basic GUI produced in stage three forms a shell, which encompasses the GIS and the expert system; thus, offering the appearance and functionality of a single decision-making system.

All the processes of the SDSS originate from the GUI and the associated Visual Basic code. The GUI serves as a communication node between the expert system and the GIS, and is used to convert data and transfer information from one system to the other. The tasks of spatial analysis and logical reasoning are performed by the GIS and the expert system. The results of these analyses are presented to the user through the GUI, which again is used to properly format the output information, in order to provide the user with an effective display of oil spill response information.

CHAPTER 5

Implementation and Case Studies

The outcome of this research is a prototype Spatial Decision Support System (SDSS) for oil spill response in Anaktalak Bay, Labrador. This Chapter is comprised of a discussion of the functional capabilities of the prototype, and the results of four annotated examples, each representing different potential oil spill situations. These case studies vary with regards to the location of the spill, the type and amount of spilled oil, and environmental conditions at the time of the spill. Differing spill locations and conditions result in varying combinations of coastal areas being affected, and subsequently each situation requires individualized response options.

5.1 Implementing the Spatial Decision Support System (SDSS)

The completed SDSS consists of a single executable program (ABSDSS.EXE). Initiating the Anaktalak Bay SDSS executable calls the Visual Basic module, which serves as the framework for the system. When the system is first implemented, a series of windows prompt the user for information concerning the oil spill. Any prompts requiring numeric inputs offer the user a choice of measurement units to select from before entering values in the selected format. Most input choices are presented in a drop-down menu format, which simplifies the input process for the user.

During the processing sequence of the SDSS (Figure 5.1) the user is never required to access any data or perform any complicated analysis tasks. All data access and processing inside the GIS is controlled by the embedded script, which makes complex GIS functions transparent to the user. The user is only required to provide specifically requested information concerning the oil spill.

Spatial analysis functions of the GIS automatically process the user input and spatial data. The user is periodically updated through message boxes, which explain the type of analysis that is taking place and what the analysis has discovered. For example, as shown in Figure 5.2, the user is informed when the bearing and speed of oil slick have been calculated. Also, once the at-risk coastal segments are identified, the user is notified of the number of segments in the path of the slick and the total length of the affected coastline.

The newly generated advice and information – the main output of the SDSS – is displayed through the GUI. The user can cycle backwards and forwards through information relating to each individual coastal area and the oil spill in general. A new report type can be viewed at any time during the information viewing session, and any reports can be saved to individual text files at the user's request. Output information can be viewed for an unlimited time period, until all advice and options have been explored to the user's satisfaction.

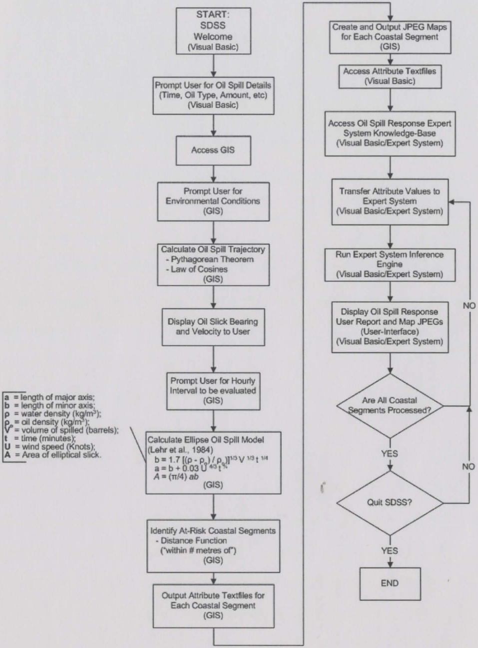


Figure 5.1: Flow chart of SDSS implementation and processing

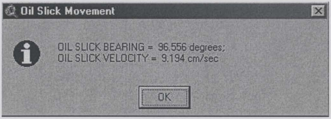


Figure 5.2: Oil slick information output from the GIS

5.2 Annotated Examples

Four oil spill scenarios are presented to illustrate a variety of possible circumstances that could be encountered by an oil spill response SDSS. Spill scenarios were developed to demonstrate the variety of potential response operations that may be required based on varying combinations of oil spill events and environmental conditions (see Table 5.1); and also to examine the capacity of the SDSS to communicate both small and large amounts of knowledge and data.

The scenarios vary with regards to the ocean current speed and direction, the wind speed and direction, the type and amount of oil, and the location of spilled oil. Varying wind and ocean surface conditions, in particular, can cause the spill trajectory and area of influence to change substantially. As a result, the extent of coastal area and types of environments that will be affected can change drastically. The same spill under slightly different conditions can produce a number of different outcomes, each requiring individualized protection and treatment plans.

Table 5.1: SDSS input values used for the four oil spill scenarios.

Input	***Spill Scenario # 1***	***Spill Scenario # 2***	***Spill Scenario # 3***	***Spill Scenario # 4***
	Initial Input Values			
Type of Oil	Fuel Oil No. 2 (Diesel)	Fuel Oil No. 2 (Diesel)	Fuel Oil No. 4	Fuel Oil No. 4
Amount of Oil	500 Barrels	500 Barrels	25 Barrels	5000 Barrels
	GIS Input Values			
UTM Easting	557960m E	557960m E	564183m E	564183m E
UTM Northing	6254202m N	6254202m N	6256203m N	6256203m N
Ocean Current Speed	5 cm/sec	5 cm/sec	7 cm/sec	7 cm/sec
Wind Speed	5 Knots	8 Knots	6 Knots	20 Knots
Ocean Current Bearing	158 degrees (towards)	158 degrees (towards)	158 degrees (towards)	158 degrees (towards)
Wind Bearing	95 degrees (towards)	275 degrees (towards)	95 degrees (towards)	95 degrees (towards)
Evaluation Time	10 hours	10 hours	10 hours	10 hours
Evaluation Interval	2 hours	2 hours	2 hours	2 hours

In spill scenarios #1 and #2 (Figure 5.3), the spills occur at the same location in a somewhat confined area of Anaktalak Bay, and involve the same type and amount of oil. The difference between these two scenarios is the wind speed and wind direction. These variations, particularly wind direction, produce two distinct oil spill events, which require different coastal areas to be protected and treated, as demonstrated by the SDSS output.

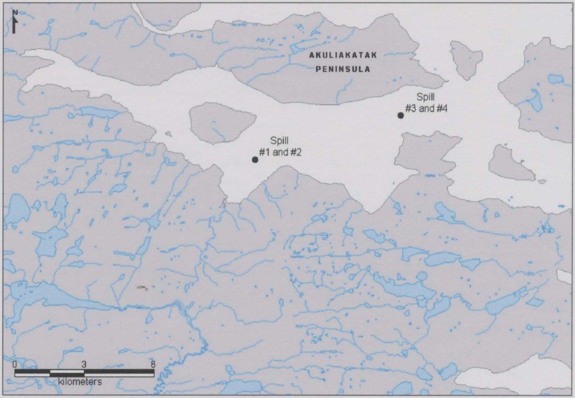
Spill scenarios #3 and #4 take place in the same location, although at a different location than scenarios # 1 and # 2, and in an unconfined area of Anaktalak Bay. Two major variables are altered in these two scenarios - the amount of oil and the wind speed. Spill # 3 is a small-sized spill, which occurs during average weather conditions while spill # 4 is a large-scale spill that takes place during storm-type wind conditions. Additionally, spill #4 involves the added complication of a change in wind conditions during the implementation stage of the oil spill response proceedings.

For comparative purposes, each annotated spill example will be evaluated based on a 10 hour time period, with a 2-hour evaluation interval, and a constant ocean current bearing.

5.2.1 Spill Scenario # 1

Spill Scenario #1 consists of a 500 barrel sized spill occurring in open water, under average wind and ocean current conditions. The spill takes place at 8:00 PM, and is located at 6254202m N and 557960m E (Figure 5.3), along the Anaktalak Bay shipping route (Figure 5.4). The area surrounding the spill location is somewhat confined to the east and to the west by the upper extent of Edward's Cove. The spill source is a ship

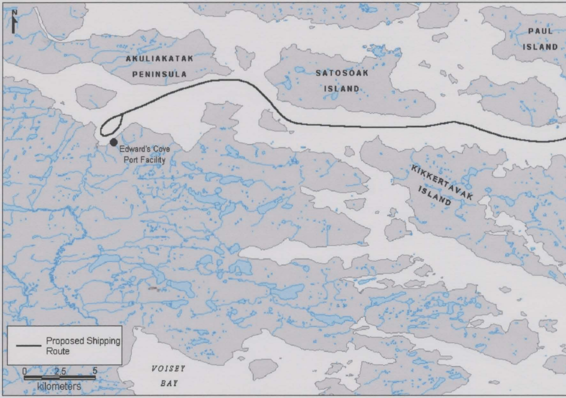
56°28' N
62°09' W



56°22' N
61°51' W

Figure 5.3: Location of four oil spill scenarios used to evaluate the SDSS.

56°60' N
62°11' W



56°15' N
61°33' W

Figure 5.4: Proposed shipping route to the Edward's Cove Port Facility.

travelling towards the Edward's Cove port facility carrying 5000 tons of fuel oil for use at the Voisey's Bay mine and mill site. The oil spill occurs as a result of a minor hull breach caused by a collision with an ice flow.

The conditions of the oil spill are as follows:

- Time of spill: 8:00 PM
- Location (UTM coordinates): 6254202m N, 557960m E
- Oil type: Diesel Fuel (Fuel Oil No. 2)
- Oil amount: 500 barrels
- Wind speed: light (5 Knots)
- Wind bearing: westerly (towards 95°)
- Ocean current speed: weak (5 cm/sec or 0.18 km/hr)
- Ocean current bearing: from NNW to SSE (towards 158°)

Once the spill has been identified, there are five key steps that precede the implementation of protection and cleanup operations (The International Tanker Owners Pollution Federation Ltd., 1986; Etkin, 1990):

(1) Notification;

(2) Evaluation;

(3) Response decision-making;

(4) Mobilization;

(5) Deployment.

These steps should be fully executed within 24 to 48 hrs, depending on the distance from the response site to the oil spill, and the environmental conditions at the time of the spill (DeCola, 2000). Step two and Step three employ the SDSS. Activating the SDSS immediately prompts the user for initial input data. All input values used in the annotated examples are provided in Table 5.1.

Using the initial input and GIS input, the GIS calculates the bearing and speed of the predicted oil slick to be 96.556° and 9.194 cm/sec (0.179 Knots) respectively (Figure 5.2). These values are then used to calculate the elliptical spread of the oil slick for a specified evaluation period. In this case, and also the following scenarios, a 10 hr evaluation period is used. The spills occur within 10 km of the Edward's Cove Facility, which functions as a temporary oil spill response facility, therefore response operations should be implemented fairly rapidly. The Anaktalak Bay area is a geographically confined space and, therefore, most spilled oil will encounter a coastline within a few hours of the initial spill.

Once the elliptical oil spill model has been calculated, the GIS queries the coastal database and identifies the coastal areas at risk of oil spill contamination (Figure 5.5). As determined by the SDSS, six coastal segments, measuring a total of 6637.5 m in length and ranging from 5 to 70 m in width, could potentially be affected as a result of the oil spill. Three segments are directly in the path of the predicted oil slick, while the remaining three segments are located within 200 m of the slick, and therefore could easily become affected if conditions change slightly.

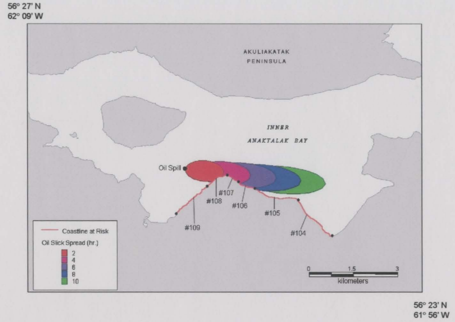


Figure 5.5: Predicted oil spill spread and affected coastal area for oil spill scenario # 1.

After the GIS-based analysis, control is returned to Visual Basic, which now processes data through the expert system. For each segment of the selected coastline, the expert system fires between 62 and 68 rules in a matter seconds seconds, the results of which can be viewed in the user reports. The user is prompted to select a type of report for viewing and evaluation (Figure 4.9). The reports are displayed in the main window of the GUI, in combination with maps depicting the extent of the spill and the affected coastline (Figure 5.6).

The output for oil spill scenario # 1 consists of a total of 25 possible reports, as produced by the expert system, that the user can evaluate (see Appendix A for sample reports). The *General Information* report describes the oil spill event including the date,

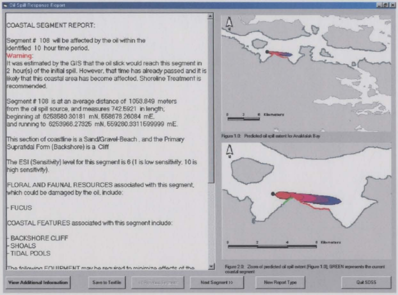


Figure 5.6: SDSS user-interface depicting *Summary* report output for segment # 109 in Spill Scenario #1

time, type of oil, and conditions of the spill (Figure 5.7). Additionally, a brief description of Diesel fuel informs the user that this type of fuel spreads quickly and exhibits a fairly rapid rate of natural removal from the ocean surface; however, if coastal areas are affected the pollution can persist for some time.

The *Summary* reports produced by the SDSS describes the status of each segment within 200 m of the oil spill area, in addition to a list of equipment that may be required during response operations (Figure 5.8). According to the SDSS, three of the identified segments are not in the direct path of the slick and therefore do not require immediate attention. The predicted spill model identifies one segment (Segment # 108) (Figure 5.9) of the remaining three that has already been affected by the spill within the 2 hrs

```
GENERAL INFORMATION:

DATE:      June 3, 2003

LOCATION OF SPILL: 6254202 mN, 557960 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 10 minutes

SPEED OF OIL SLICK MOVEMENT: 0.179 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 96.556 degrees

TYPE OF OIL: Diesel (Fuel Oil No. 2)

Diesel is a light viscosity oil, and therefore will spread
quickly. Diesel is a low to medium density oil and should be
naturally removed from the ocean surface in less than a week.
However, any pollution of coastal resources or features could
persist, and treatment needs should be assessed.

     API: 34.5
     POUR POINT: -15
     FLASH POINT: 180


VOLUME OF OIL SPILLED: 79.49 Cubic Meters

AFFECTED COASTLINE: 6 Coastal segments may become affected by the
spill; 3 of these segments are directly in the path of the oil
slick, while 3 of these segments are not within the direct path,
but are located within 200 meters of the slick and therefore may
be at risk.

WIND DIRECTION (Towards): 95 degrees

WIND SPEED: 5 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45
```

Figure 5.7: General Information report produced by SDSS for oil spill scenario # 1.

```
COASTAL SEGMENT REPORT:

Segment # 108 will be affected by the oil within the identified 10
hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this
segment in 2 hour(s) of the initial spill. However, that time has
already passed and it is likely that this coastal area has become
affected. Shoreline Treatment is recommended.

Segment # 108 is at an average distance of 2930.349 meters from
the oil spill source, and measures 742.5921 in length; beginning
at 6253580.30181 mN, 558678.26084 mE,
and running to  6253966.27325  mN, 559280.3311599999  mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary
Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 6 (1 is low
sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which
could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF
- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the
spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming
operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment
```

Figure 5.8: Sample Coastal Segment Summary Report produced by the oil spill response SDSS for spill scenario # 1.

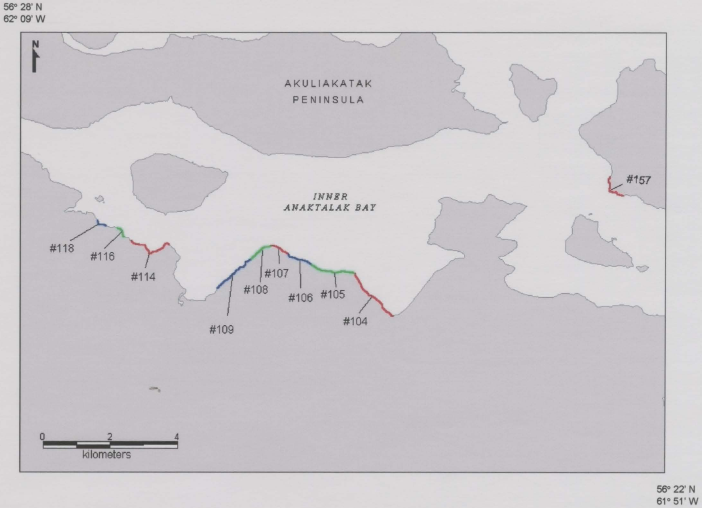


Figure 5.9: Selected coastal segments, including ID values, identified by the oil spill response SDSS for the four oil spill scenarios.

and 10 min since the spill occurred. According to the logical rules of the SDSS, this segment will require treatment, while the two segments that have not yet been affected (Segments # 06 and # 107) will require protection efforts. However, it is predicted that Segment # 107 will become affected at 2 hrs and 20 min from the initial spill, leaving little time to implement protection operations. Therefore, it will be necessary to prepare shoreline treatment operations for this segment.

After implementing the SDSS and prior to beginning protection and cleanup techniques, phases four and five of the oil spill response take place; mobilization and deployment. First, the necessary equipment and personnel must be mobilized. Next, all equipment and personnel are deployed to the oil spill site. The amount of time required for deployment will depend on the distance from the response site to the oil spill, and also on current weather conditions.

Upon arriving at the site protection techniques are implemented first in order to prevent further contamination of any coastal areas. Once protection operations are in place, collection of oil, and cleanup of oiled shorelines can begin.

Segment # 106 (Figure 5.9), which will require immediate protection, is a boulder beach with a backshore cliff, and also includes tidal pools. At 2:10 hrs from the initial spill, this segment has not yet been affected, but will likely become affected within 4 hrs of the spill; therefore, shoreline protection is the objective. The recommended protection technique for this area of coastline, as identified by the expert system, is nearshore redirection of oil away from the coastline. Additional protection options include exclusion booming and contact barriers.

Segment # 107 (Figure 5.9), which requires treatment, is a bedrock coastline with a backshore cliff. The SDSS identifies multiple options for this segment, with natural recovery and low-pressure cold-water wash being the preferred treatment techniques. Additional treatment possibilities include flooding, low-pressure warm-water wash, high-pressure cold-water wash, vacuum recovery, vegetation removal, dispersants, shoreline cleaners, solidifiers and bioremediation. For small amounts of oil, manual removal or passive sorbents are also suggested.

Segment # 108, which will also require treatment, is described as a sand and gravel beach with a backshore cliff, and additional coastal features including shoals and tidal pools. According to the knowledge-base, natural recovery is the only viable recommended treatment option for this area; mechanical recovery would be recommended, however, this shoreline is not suitable for large machinery. If more direct treatment action is preferred several optional treatment techniques are described including flooding, low-pressure cold-water wash, vacuum recovery, vegetation removal, dispersants, shoreline cleaners, solidifiers and bioremediation.

5.2.2 Spill Scenario # 2

Spill Scenario # 2 repeats the same spill event as was described in spill scenario # 1 (see above), but with slight variations in the environmental conditions at the time of the spill. *Spill Scenario # 2* consists of a 500 barrel sized spill occurring in open water, under average wind and ocean current conditions. The spill takes at 8:00 PM, and is located at 6254240m N and 557923m E (Figure 5.3). The area surrounding the spill is partially confined to the east and to the west by the upper extent of Edward's Cove. The oil spill is, again, the result of a minor hull breach caused by impact with a seasonal ice flow.

The conditions of the oil spill are as follows:

- Time of spill: 8:00 PM
- Location (UTM coordinates): 6254202m N, 557960m E
- Oil type: Diesel Fuel (Fuel Oil No. 2)
- Oil amount: 500 barrels (approximately 79 000 liters)
- Wind speed: 8 Knots (14 km/hr)
- Wind bearing: easterly (towards 275°)
- Ocean current speed: weak (5 cm/sec or 0.18 km/hr)
- Ocean current bearing: from NNW to SSE (towards 158°)

As soon as details of the oil spill have been determined, the appropriate authorities are notified, and the oil spill response SDSS is activated, spill response proceedings can be initiated.

According to the *General Information* report produced by the expert system (Figure 5.10), the resulting oil slick is spreading at a rate of 13.2 cm/sec (0.259 Knots), at a bearing of 273.45° (towards). As indicated by the *Summary* reports, a total of eight coastal segments, measuring a total of 6433.3 m in length and ranging from 5 to 100 m in width, are in the path of the slick. Seven of the identified coastal segments are in the direct path of the oil slick, while one is within 200 m of slick predicted by the GIS-based model (Figure 5.11). The segment that is not in the direct path of the slick belongs to an

GENERAL INFORMATION:

DATE: September 23, 2003

LOCATION OF SPILL: 6254202 mN, 557960 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 15 minutes

SPEED OF OIL SLICK MOVEMENT: 0.259 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 273.445 degrees

TYPE OF OIL: Diesel (Fuel Oil No. 2)

Diesel is a light viscosity oil, and therefore will spread quickly. Diesel is a low to medium density oil and should be naturally removed from the ocean surface in less than a week. However, any pollution of coastal resources or features could persist, and treatment needs should be assessed.

API: 34.5
POUR POINT: -15
FLASH POINT: 180

VOLUME OF OIL SPILLED: 79.49 Cubic Meters

AFFECTED COASTLINE: 8 Coastal segments may become affected by the spill; 7 of these segments are directly in the path of the oil slick, while 1 of these segments are not within the direct path, but are located within 200 meters of the slick and therefore may be at risk.

WIND DIRECTION (Towards): 275 degrees

WIND SPEED: 8 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45

5.10 General Information report produced by SDSS for oil spill scenario # 2.

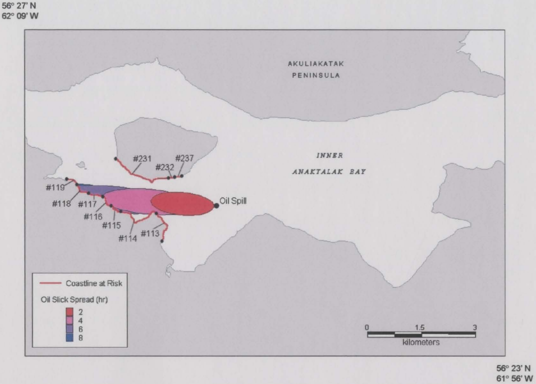


Figure 5.11: Predicted oil spill spread and affected coastal areas of oil spill scenario # 2.

offshore island located in the center of the bay. The fuel type that was spilled is, again, diesel (Fuel Oil No. 2), which spreads quickly, but is also removed fairly quickly from the ocean's surface by natural methods. However, again, if diesel oil does come in contact with the shoreline it can persist for extended periods, and in such cases treatment may be necessary.

According to the individual coastline *Summary* reports, seven of the eight identified coastal segments are sand and gravel beaches, while the remaining segment is a boulder beach. Additionally, Segment # 118 (Figure 5.11) contains an estuary, which is considered a sensitive area. After two hours of oil slick movement, none of the segments.

will be affected, which indicates that protection operations are currently the best option for these coastal areas. However, it is predicted that the spill will reach Segment # 114 – a sand and gravel beach – after 2:40 hours, therefore treatment will potentially be required for this section of coastline, depending on the amount of time required for mobilization and deployment.

According to the *Shoreline Treatment* report the recommended treatment techniques for Segment # 114 (Figure 5.11) are natural recovery or mechanical recovery. Additional optional treatment techniques include flooding, low-pressure cold-water wash, vacuum recovery, vegetation removal, dispersants, shoreline cleaners, solidifiers or bioremediation.

For the six remaining segments in the direct path of the oil slick, the SDSS recommends protection operations, which should be considered high priority, in order to prevent additional coastal areas from becoming contaminated. The boulder beach area (Segment # 116) should be considered the highest priority, as boulder beaches can be difficult to clean when oil seeps between boulders. The recommended protection technique for this segment is redirection of oil away from the shore. Optional protection techniques identified from the knowledge-base include exclusion booming and contact barriers.

Redirection of oil towards the coastline is the suggested technique for the remaining coastal segments. However, the SDSS also indicates the presence of shoals in these areas, which the expert system identifies as potential obstacles for near-shore booming operations. Depending on the coastal area at risk, additional options suggested from the knowledge-base include various combinations of exclusion booming, contact barriers, shoreline protection booming and shoreline barriers. Also, for Segment # 118 (Figure 5.11), which contains an estuary, the *Shoreline Protection* report identifies the additional objective of preventing transport of the oil into the estuary, which can be accomplished using exclusion booming.

5.2.3 Spill Scenario # 3

Spill Scenario #3 is representative of a small oil spill, influenced by moderate wind and surface current conditions. The spill takes place at 8:00 PM, and is located at 6256203m N and 564183m E (Figure 5.3). Unlike the previous two scenarios, this spill occurs at a location that is relatively unconfined to the East and West, which are the predominant wind directions and therefore the most likely directions of oil spill movement. Also, the size of the spill is much smaller than spills # 1 and #2, and the oil type is of a higher viscosity. The source of the spill is a transport vessel travelling towards the Edward's cove port facility carrying 5000 tons of fuel oil for use at the Voisey's Bay mine and mill facility. The oil spill occurs in the evening when the ship strays from the surveyed shipping route and grazes a submerged rock.

The conditions of the oil spill are as follows:

- Time of spill: 8:00 PM
- Location (UTM coordinates): 6256203m N, 564183m E
- Oil type: Fuel Oil No. 4
- Oil amount: 25 barrels (approximately 3950 liters)
- Wind speed: 6 Knots (11.1km/hr)

- Wind bearing: westerly (towards 95°)
- Ocean current speed: weak (7 cm/sec or 0.136 knots)
- Ocean current bearing: from NNW to SSE (towards 158°)

The SDSS is activated and the appropriate authorities are notified of the event, once initial information pertaining to the oil spill has been collected.

According to the *General Information* report (Figure 5.12) the oil slick is moving at 0.205 Knots in an easterly direction (towards 96.55°). Based on spatial calculations of within the GIS oil spill model, one coastal segment, measuring a total of 884.2 m in length and 25 m in width, is identified in the direct path of the predicted oil slick (Figure 5.13).

Output from the expert system, as presented in the *General Information* user report, indicates that Fuel Oil No. 4 is a medium viscosity oil with a medium to high density, that will spread fairly rapidly and has the potential to persist in the environment for months. Protection and treatment operations are encouraged in order to minimize damages.

Protection is the priority for this response operation. According to the *Summary* report, the predicted oil slick will reach this area at approximately 9:20 hrs after the initial spill; therefore protection of the coastline is possible. The *Summary* report identifies the coastal segment at-risk (Segment # 157) (Figure 5.11) as a sand and gravel beach with a backshore wetland area. Shoals and tidal pools are also present along this coastal segment.

```
GENERAL INFORMATION:

DATE: September 23, 2003

LOCATION OF SPILL: 6256203 mN, 564183 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 10 minutes

SPEED OF OIL SLICK MOVEMENT: 0.205 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 96.55 degrees

TYPE OF OIL: Fuel-Oil-No.-4

Fuel Oil No. 4 is a medium viscosity oil and therefore will spread
fairly quickly. Fuel Oil No. 4 is a medium to high density oil and
could persist in the environment for months; protection, treatment
and/or cleanup may be necessary.

     API: UNKNOWN
     POUR POINT: -3
     FLASH POINT: 78

VOLUME OF OIL SPILLED: 3.97 Cubic Meters

AFFECTED COASTLINE: 4 Coastal segment(s) may become affected by
the spill; 1 of these segments are/is directly in the path of the
oil slick, while 3 of these segments are not within the direct
path, but are located within 200 meters of the slick and therefore
may be at risk.

WIND DIRECTION (Towards): 95 degrees

WIND SPEED: 6 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45
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Figure 5.12: General Information report produced by SDSS for oil spill scenario # 3

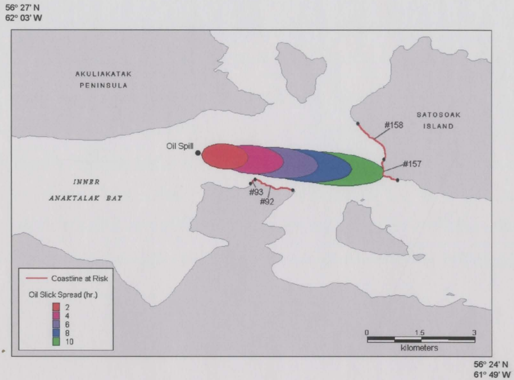

Figure 5.13: Predicted oil spill spread and affected coastal areas of oil spill scenario # 3.

The *Shoreline Protection* report recommends both redirection of oil towards the coastline and shoreline barriers as appropriate protection techniques. Sand and gravel beaches in areas of high exposure levels exhibit low sensitivity to oil retention, and therefore it is relatively safe to allow for oil collection at the shoreline. Optional protection techniques include exclusion booming, shoreline protection booming or shoreline barriers. However, due to the presence of shoals, booming operations near the shore may be difficult.

5.2.4 Spill Scenario # 4

Spill Scenario # 4 occurs at the same location as spill scenario # 3, but the size of the spill and the environmental conditions have changed to produce a very different oil spill. Additionally, during this scenario the wind conditions change drastically, which alters the movement of the spill during the response proceedings. The spill takes place at 8:00 PM, and is located at 6256203m N and 564183m E (Figure 5.3). The source of the spill is a transport vessel traveling towards the Edward's Cove port facility carrying 5000 tons of fuel oil for use at the Voisey's Bay mine and mill facility. The oil spill occurs at night when the ship grazes a submerged rock causing an extensive hull breach.

The conditions of the oil spill are as follows:

- Time of spill: 8:00 PM
- Location (UTM coordinates): 6256203m N, 564183m E
- Oil type: Fuel Oil No. 4
- Oil amount: 5000 barrels
- Wind speed: 20 Knots (37.04 km/hr)
- Wind bearing: westerly (towards 95°)
- Ocean current speed: weak (7 cm/sec or 0.136 knots)
- Ocean current bearing: from NNW to SSE (towards 158°)

Processing the details of the oil spill using the SDSS identifies a total of 17 segments in the path of the oil slick. According to the *General Information* report, the oil slick is moving at 0.615 Knots in an easterly direction (towards 96.55°) (Figure 5.14). As presented in the *Summary* reports produced by the expert system, 15 of the 17 segments are in the direct path of the oil slick while the remaining two are within 200 meters of the spill. As in Spill Scenario # 3, Fuel Oil No. 4 is the pollutant. The viscosity-level of this oil, in combination with weather conditions, causes the oil to spread at a moderately rapid rate. This oil has the potential to persist in the environment for months; therefore, protection and treatment operations are encouraged in order to minimize damages.

According to the spatial attribute data extracted from the GIS, twelve of the 17 segments in the path of the oil slick are characterized as sand and gravel beaches, two are

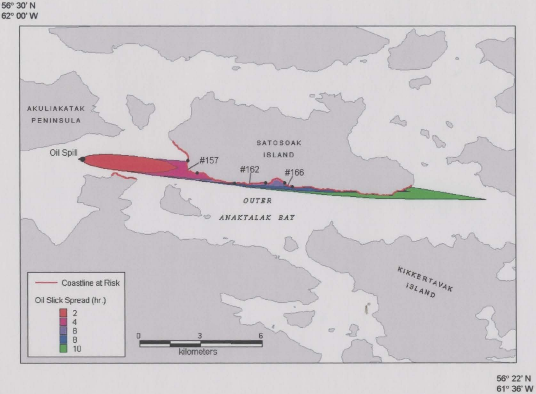

Figure 5.14: Predicted oil spill spread and affected coastal areas of oil spill scenario # 4.

sand beaches, one is bedrock, one is a boulder beach and one is a sand flat. None of the identified coastal segments will be affected by oil slick within two hours of the initial spill. However, it is predicted that Segment # 157 (Figure 5.14) will be affected within 2:20 hrs of the spill; therefore treatment will be necessary for this segment.

Segment # 157 is a sand and gravel beach with a backshore wetland, in addition to the presence of shoals and tidal pools. In this case, the main objective for coastline treatment, as determined from the SDSS, is to minimize damage to the marsh area. According to the *Shoreline Treatment* report (Figure 5.15), the recommended treatment techniques are natural recovery and mechanical recovery. However, based on the knowledge contained in the expert system, the user is warned to undertake mechanical removal of sediment with caution because "excessive removal of coarse sediment should be avoided, as natural replacement rates are very slow" (see Appendix A). Optional treatment techniques presented in the user report include flooding, low-pressure cold-water wash, vacuum recovery, vegetation removal, dispersants, shoreline cleaners or solidifiers. Manual removal, passive sorbents, tilling or aeration, and surf washing or sediment reworking are options for small amounts of oil.

Protection operations will be required for the remaining 14 coastal segments located in the direct path of the modeled slick, and should be implemented as early as possible after the spill. Of these coastal areas, segments # 162 and #166 (Figure 5.14) are

SHORELINE TREATMENT FOR SEGMENT # 157 (6255444.28241 mN, 569728.69819 mE TO 6255992.26087 mN, 569343.71621 mE):
*To be carried out if the oil slick reaches the shoreline

Segment # 157 is at an average distance of 5312.047 meters from the oil spill source.
The oil slick will reach this segment within approximately 2.33 hour(s) of the initial spill.

SHORELINE TREATMENT OBJECTIVES:
(ie. the goals for an effective shoreline clean-up operation)

- Minimize operational damage to dune, marsh or peat bog areas

SHORELINE TREATMENT STRATEGIES:
(ie. actions that should be taken if the shoreline segment comes in contact with the oil slick)

- Minimize waste generation using in-situ techniques
- Manual techniques are preferred

RECOMMENDED SHORELINE TREATMENT OPTIONS:
(ie. the best treatment options for dealing with a shoreline segment that has come into contact with the oil slick)

- **Natural Recovery**

Natural Recovery means allowing the coastal area to recover naturally, and should always be considered the preferred option.
It is generally necessary to monitor the location to ensure that the assessment is correct or that conditions do not change.
This technique is implemented when:
(a) the cleaning options have the potential to cause more damage than they prevent,
(b) response techniques will not accelerate natural recovery or,
(c) response operations could place cleanup personnel in danger.

- **Mechanical Recovery**

Mechanical Removal uses mechanical equipment to remove oil and oiled materials.
Each type of equipment has a particular application:
- Scrapers and graders can operate only on hard and relatively flat surfaces and are capable of moving only a thin cut (~10 cm) of surface material.
- Loaders, bulldozers and backhoes can operate in a wider range of conditions and are designed to dig and remove large volumes of material. * Front-end loaders are the preferred type of equipment for this type of shoreline because of generally poor traction.
Backhoes are an alternative choice.
- Backhoes, draglines and clamshells use an extending arm or crane so that they may be operated from a barge or from a backshore area and can reach to pick up material.
- Beach cleaning machines can operate either directly on a beach or off-site to treat oiled sediments.
- Vacuum trucks remove pooled oil or oil collected in sumps.
Test runs or trials with experienced equipment operator will determine which machines are best suited.

Figure 5.15: Shoreline Treatment report, for segment # 157 produced by the SDSS for oil spill scenario # 4

the most sensitive, with Environmental Sensitivity Index (ESI) values of 9 and 8 respectively[4]. According to the SDSS predictions, Segment # 162 will be affected after 5:20 hrs, while segment # 166 will be affected after 5:40 hrs; therefore protection is viable for both coastal areas.

As identified from the GIS data, Segment # 162 is a sand flat with a beach backshore, and is bordered by shoals and tidal pools. Segment # 166 is a bedrock coastline with a wetland backshore, and is also bordered by shoals and tidal pools. Redirection away from the coastline is a recommended protection technique for both coastal areas. Additionally, for Segment # 166, exclusion booming is a protection option. However, the SDSS has noted the presence of shoals, which in combination with high wind speeds, will make booming operation difficult if not impossible. Consequently, protection of these, and other, coastal segments may be impossible under the given conditions, and hence treatment may be required at a later time.

Four hours after the initial oil spill, the wind direction within Anaktalak Bay changes drastically from westerly to easterly as the storm moves north along its track. The oil slick responds to the altered environmental conditions, and also changes directions. The SDSS is not currently able to handle changing conditions in a single run, however, a second run of the SDSS produces a reliable calculation of the oil slick's new trajectory, and identifies the required response options for the new areas of threatened coastline.

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[4] Based on a basic Environmental Sensitivity Index (ESI); where 1 represents low sensitivity, and 10 represents high sensitivity.

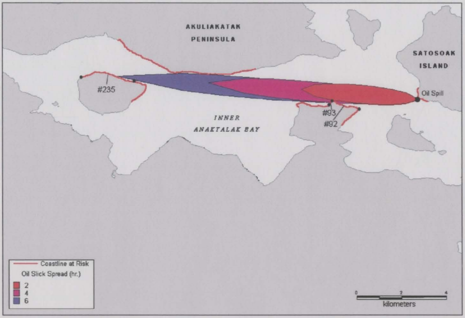
The second run should be considered a continuation of the first processing run. The new spill prediction is initiated from the center of the most recent location of the original spill. This initial location is positioned at the center of the 4-hour ellipse, produced from the first SDSS run, which represents the thickest mass of oil after 4 hrs of spreading. The oil slick that is trailing from this core consists primarily of a thin, sheen layer of oil. After 4 hrs of spreading only a small proportion of the 5000-barrel spill would have dissipated, therefore, the initial size of the spill is maintained for the second spill run. In order to evaluate the full ten-hour time period, as in the previous spill scenarios, a six-hour period is selected to run the new oil spill model, as a continuance of the four-hour original spill.

The conditions of the secondary oil spill are as follows:

- Time of spill: 24:00 (12:00 AM)
- Location (UTM coordinates): 6255610m N, 569185m E
- Oil type: Fuel Oil No. 4
- Oil amount: 5000 barrels
- Wind speed: 20 Knots (37.04 km/hr)
- Wind bearing: easterly (towards 275°)
- Ocean current speed: weak (7 cm/sec or 0.136 knots)
- Ocean current bearing: from NNW to SSE (towards 158°)

According to the *General Information* report, the secondary oil slick is moving at 0.615 Knots in an easterly direction (towards 273.45°) (Figure 5.16) The SDSS

56° 27' N
62° 09' W



56° 22' N
61° 51' W

Figure 5.16: Predicted oil spill spread and affected coastal areas of secondary oil spill for scenario # 4.

calculations identify a total of ten coastal segments, which may be affected by the oil spill. Six of the identified segments are located in the direct path of the oil slick, while the remaining four are within 200 m of the slick.

Five of the ten identified segments are characterized as sand and gravel beaches, two are bedrock, two are boulder beaches and one is a sand flat. None these segments will be affected within the initial two hours of the wind change, excluding segment # 157, which is the origin of the secondary spill and was addressed in the first SDSS run.

Segments #92 and #93 (Figure 5.16) will be affected at approximately 2:20 hrs after the wind change, and therefore will possibly require treatment.

Segment #92 is a sand and gravel beach with a backshore wetland. The only treatment technique recommended by the SDSS for this segment is natural recovery. Additional optional treatments include flooding, low-pressure cold-water wash, vacuum recovery, vegetation removal or cropping, dispersants, shoreline cleaners, solidifiers and bioremediation. If only a small amount of oil is present on the shore then manual removal is a preferred technique. The user is warned against using mechanical recovery due to the sensitive nature of the shoreline.

Segment #93 is a boulder-beach with a backshore cliff, and also river channel. Recommended treatment techniques for this segment are natural recovery and low-pressure cold-water wash. Optional techniques include low-pressure warm-water wash, high-pressure cold-water wash, vacuum recovery, vegetation removal or cropping, burning, dispersants, shoreline cleaners, solidifiers and bioremediation. Again, if only a small amount of oil has reached the shore then manual removal is also recommended.

The remaining segments will require protection operations. Segment #235 (Figure 5.16) should be highest priority for protection because of its high sensitivity value (ESI = 9). Segment #235 is a sand flat with a backshore beach, and is also lined by shoals and tidal pools. The recommended protection technique for this section of coastline is redirection of oil away from the shoreline, which can be accomplished using a variety of boom configurations. Optional techniques include exclusion booming, shoreline protection booming and shoreline barriers. The presence of shoals may complicate near shore booming operations.

5.3 Summary

The oil spill response SDSS successfully evaluated the four oil spill scenarios and rapidly produced response information specifically relevant to each situation. The integration of the GIS and the expert system was a logical union, which proved effective for combining the data and knowledge that are integral components for effective oil spill response decision-making.

The above case studies, however, greatly simplify the intricate internal processing of the SDSS. To the user, the calculations and logical processes of the system are transparent. The user is only presented with data and knowledge directly relevant to the current situation, which is a crucial component for a successful SDSS. In actuality, the internal functions of the SDSS are complex, involving an extensive database, multiple spatial calculations and several hundred action table rules.

Traditionally, evaluating an oil spill response situation would be a time-consuming undertaking for an oil spill expert, or multiple oil spill professionals. However, with the SDSS, the same data and knowledge can be accessed and processed by an inexperienced user, in order quickly formulate and implement a viable oil spill response plan.

CHAPTER 6

Discussion and Conclusion

The objective of this research was to develop a prototype SDSS for coastal zone oil spill response in Anaktalak Bay, Labrador. The final product is a operative system that combines the spatial analysis functions of the GIS and the logical reasoning capabilities of the expert system into a single decision-making tool. The following discussion reviews the functional capabilities of the completed system and the results of the four annotated examples presented in the previous chapter.

6.1 Discussion of Results

As demonstrated by the examples in chapter five, the prototype SDSS runs efficiently, is easy to use, and produces straightforward, useful information. The graphical user interface (GUI) linkage between the GIS and the expert system effectively communicates all necessary data between the two systems. This linkage provides the means for integrating knowledge and data that is fundamental to oil spill response decision-making. The transfer of data occurs quickly and is transparent to the user, therefore hiding the complexities of the system. Automated data access eliminates any need for the user to examine the extensive database associated with the coastline, which instead is automatically queried based on the spatial relationships between the coastal segments and the calculated oil slick. The contents and analysis functions of a GIS are considered beyond the capabilities of average computer users. However, these users can quickly and easily access the same data and tools using the SDSS, in addition to the knowledge contained in the expert system. These decision-making tools should significantly simplify and enhance response procedures for oil spill response personnel, and thereby minimize the potential for negative consequences.

Based on initial testing of the SDSS, the system appears to function effectively and produce relevant information. However, further system testing will be a necessity in the future. The oil spill response SDSS produced through this research is still in the early stages of development, and will require modifications and enhancements before it can be considered a fully operative SDSS. The final system will need to undergo more intensive field testing, particularly by potential users, such as oil spill response personnel and oil spill response experts. The prototype SDSS developed in this research, however, indicates the obvious potential for the use of such a system, and additionally demonstrates the advantages of linking the GIS and expert system for decision-making purposes.

Within the GIS, representation of the coastline as a segmented linear feature proves effective for the identification of at-risk coastal areas. The linear model is a common form for depicting coastlines, and is familiar and recognizable to users. Coastal segments are easily identified in the SDSS using maps, unique ID numbers and geographical coordinates. Affected coastal segments are distinguished on the SDSS maps by varying colours, and also through individual maps provided for each segment.

Originally, the intended form for the Anaktalak Bay database was dynamic segmentation. However, during the development of the SDSS it was determined that using dynamic segmentation is not a practical approach to coastal zone oil spill response. Measured distances along a coastline, as used in dynamic segmentation, may cause confusion during an emergency situation. Geomorphically distinct segments, as used in the linear model, are easily visible, and consequently can be quickly identified by response personnel to promote the rapid implementation of protection and cleanup operations. Hence, the coastline was best conceptualized and modeled in the SDSS as a simple linear feature with distinct geomorphological segments.

Identification and selection of the coastal segments inside the GIS was based on the predictive oil spill model. The spill model was found to effectively represent the general formation and spread of an oil slick based on time, wind and current conditions, and volume and density of oil. The model produces a series of ellipses representing the temporal spread of the oil slick extending from the spill source.

Based on multiple runs of the oil spill model it was found that higher wind speeds cause the oil slick ellipse to spread more expansively along the major axis of the ellipse, thereby creating a series of progressively longer and narrower ellipses, while extremely low wind speeds result in wider, more rounded slick formations. Figure 6.1 shows the changing ratios of the major to minor axes with respect to increasing wind speeds and increasing time since the oil spill. Within Anaktalak Bay, where ocean current speeds are extremely low, the oil spill model consistently predicted long, narrow ellipses rather than circular formations due to the predominant influence of moderate to high wind speeds.

If the wind speed is significantly greater than the current speed, as is the case in Anaktalak Bay, the calculated bearing of oil spill movement, as defined by Breuel's trajectory model (1981), will always be closer to the bearing of wind movement.

The variation in the size and shape of the predicted oil slicks for the four oil spill scenarios is representative of the variability that exists in real-world oil spill situations (Doerffer, 1992). Different combinations of oil spill conditions, particularly wind and ocean currents, will produce unique spill circumstances. The type and extent of coastal areas affected is specific to any spill event, and subsequently so are the required response

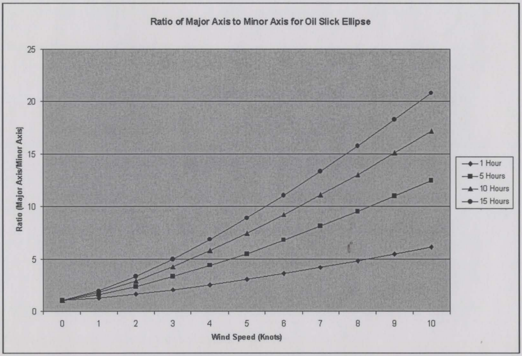


Figure 6.1: Changing ratio of major axis to minor axis of the oil spill ellipses based on time and wind speed; $\boldsymbol{\rho_o}$ = 840 kg/m3, $\boldsymbol{\rho}$ = 1000 kg/m3, $\boldsymbol{V}$ = 500 barrels.

operations. The ellipse-based model successfully represents the variability of spill movement that is essential for effective prediction of spill extent and identification of at-risk areas.

Although the ellipse-based oil spill model is effective, it is still highly generalized and does not account for the certain characteristics of oil in water behaviour, such as emulsification and evaporation. A more intricate spill model inside the GIS or a separate oil spill modeling environment would produce more realistic results. By integrating a separate modeling environment, data would be passed from the model to the GIS for further spatial processing, specifically the identification of coastal areas at risk. However, the lack of hydrographic data for the Anaktalak Bay area currently limits the extent to which a more sophisticated oil spill modeling approach can be implemented.

The spill model is also not equipped to handle changing environmental conditions, as in spill scenario # 4, which introduced the issue of changing environmental conditions. Although it is a straightforward task to run an additional oil spill scenario to determine the consequences of these new condition, the new scenario maintains no association with the previous SDSS run. Therefore, there will be no output provided relating to the shorelines that have already been affected. The user will need to refer to reports from the previous output to obtain the necessary information for treating any segments that have already been contaminated. Also, the new spill scenario will not account for movement of the oil slick that as already formed.

For the secondary spill scenario the user must determine a new location and size for the spill. It can be assumed, for the ellipse spill model, that the bulk of the remaining oil is located at the center of the current ellipse, which is the thickest area of the oil slick. The original size of the spill can be reused for the secondary scenario, if a more accurate assumption is not available. This method for dealing with changing spill conditions is only a temporary solution and is sufficient for the prototype SDSS. The obstacle of overcoming changing spill conditions does not interfere with the capability of the SDSS to communicate oil spill response knowledge and data between the expert system and the GIS. However, for future developments a more flexible oil spill model or oil spill-modeling environment would produce improved predictive results.

Additional modifications made to the GIS were fundamental in the production of the SDSS; not only for running the oil spill model, or reducing the system's complexity, but also for enabling better integration of the system. The GIS script was designed primarily to automate the functions of the GIS. The script employs the query and analysis functions of the GIS as required by the specific oil spill conditions. Additionally, it extracts the necessary data from the GIS, and alters the format of that data to meet the required input format of the expert system.

Modifying the GIS was the first step in creating the link between the GIS and the expert system. The first transfer of information occurs when the GIS exports text files containing attribute information for the identified sections of coastline. This task occurs rapidly, although processing time increases slightly as the number of identified segments increases. Creating jpegs and exporting data for 6 segments, as in scenario #1, takes approximately 15 seconds; while exporting information for17 segments, as in scenario #4, requires approximately 45 seconds.

Although, the workings of the GIS are not visible to the user, the evidence of these processes can be assessed after the SDSS has run. The text files and jpeg maps produced by the GIS are found in the SDSS folder on the computer harddrive. Spill scenario # 1 for example, produced six text files and 7 jpeg maps, where each text file corresponds to a single map, and the remaining map depicts all of the affected segments. Each of the text files contains the segment's unique ID number and a list of the segment's coastal characteristics as queried from the spatial database. The GIS output from each SDSS run is deleted at the beginning of the next run, to create space for new output; however, reports and maps can be easily saved and archived for future reference.

For the prototype system, text files were determined to be the most efficient means of transferring data from the GIS to Visual Basic and the expert system. Unformatted text files occupy a small amount space on a computer harddrive – one to two kilobytes. The simple format of these files can be easily accessed and read by other software modules, and because of their small size, only a minimal amount of memory is required to access the files. However, in a fully integrated SDSS, it would be more effective to transfer the attribute data directly from the GIS to Visual Basic or the expert system, thereby eliminating the need for intermediate files.

Additional functions of the GIS, including user input prompts and requests, are straightforward and easily comprehensible by users of any experience level. The user is not required to possess any pre-existing knowledge of the oil spill response or the affected environment. Information required from the user relates to specific conditions of the oil spill that can only be known at the time of a spill. Most input options are requested using drop-down menus or very specific instructions. If any inappropriate data are entered, a message box immediately informs the user of the problem, and requests that the data be re-entered.

The expert system also functions effectively, and successfully combines the input data with the pre-existing knowledge to produce valuable user reports. The Visual Basic ActiveX control included with the ACQUIRE® expert system significantly enhances access to the expert system by eliminating the need to launch the expert system shell. The inference engine is controlled directly through the Visual Basic platform and is capable of processing input information in a matter of seconds; a vast improvement over traditional methods.

Building the Visual Basic GUI was the most substantial component of the SDSS development. To the user the SDSS GUI appears to be a simple interface, but the real workings of the GUI are in its underlying programming, which is not visible. The GUI is the core of the SDSS and, to some extent, is always in control of the system's processing. The GIS and the expert system are temporarily invoked by the GUI to perform their specialized tasks; but control returns to the Visual Basic code once the needed data or knowledge has been acquired. This structure is fairly inflexible, particularly in terms of the user's ability to control the processing procedure. There is a concrete predefined pattern that the SDSS process follows. Although this design is somewhat rigid, it prevents the system from failing due to processing errors induced by the user's lack of skill with either the GIS or the expert system.

Despite the seemingly rigid structure of the SDSS, the linkage between the GIS and the expert system is in fact not a complete integration, and is deemed a "loose coupling". The GIS and the expert system communicate through the Visual Basic module, which creates a shell encompassing the two software components. The GUI calls each system separately, and passes data between the two, but the GIS and the expert system function as entirely separate units. It is the data and knowledge extracted from the two systems that is actually integrated, and this task is accomplished primarily by the Visual Basic GUI. The GUI collects data from the GIS, which is then organized for input into the expert system. This step is the key to the SDSS.

For the prototype SDSS, the loose coupling structure is effective; it demonstrates both the feasibility of transferring information between a GIS and an expert system, and the potential for integrating spatial data with oil spill response knowledge. However, the separation between the expert system and the GIS can lead to several functional problems for the SDSS. For example, the knowledge-base is main-memory resident, therefore, if the address of the knowledge-base is moved or missing the rules cannot be accessed. Also, the design of a loosely coupled system can be limited by shortcomings at either the front or back end of the system. In other words, if the one end (i.e. the GIS) cannot perform certain tasks then this limits the functionality of the other end (i.e. the expert system) (Smith and Yiang, 1991; Fischer, 1994). For future developments of the oil spill response SDSS, it would be advisable to develop a *tightly coupled* or fully integrated system. This type of structure would eliminate the need to physically transfer data from one piece of software to another. However, the concept of integrating knowledge and data would remain the same, whereby expert understanding in the form of logical rules is applied to extensive spatial data in order to elicit solutions to a given problem, in this case an oil spill.

The solutions produced by the oil spill response SDSS are especially relevant because of the knowledge-based aspect contributed by the expert system, which produces more realistic and human-like advice. Owens and Dewis (1995) produced a spatial database oil spill response system, which associated various response techniques with individual coastal segments inside a database. However, the association between each segment and response techniques was maintained in the database as a concrete relationship, and does not appear to change with respect to varying spill circumstances.

The expert system approach used in this research, provides a unique method of individually evaluating the attributes of each coastal area in combination with the specific oil spill conditions to logically identify the most appropriate responses for a given situation. Once solutions are identified, a user report provides a detailed account of the required actions including comprehensive explanations. In other words, the SDSS produced by this research does not simply manufacture a list of response techniques and equipment. Instead, the system provides descriptions of procedures, and explanations of the logic that lead to the formation of specific conclusions. For example, if booming is recommended but conditions are windy, then the user is warned against using booms *because* they are less effective during high winds and turbulent ocean conditions.

Detailed reports and explanations are an essential part of the oil spill response SDSS. Multiple report options offer both generalized and highly specific information to meet the varying needs the user. The reports are easily comprehensible and discuss only issues, strategies and techniques that relate to each individual coastal area. Descriptions of techniques and how to implement operations are contained in the text to ensure that the user receives a thorough explanation of the suggested procedures. The more complicated ideas and operations contained in the text are further explained in the "additional information" section of the SDSS, which can be accessed by the user at any time.

One issue that arose with regards to user reports was the quantity of output associated with large oil spills. If the predicted oil slick encountered an extensive section of the coastline, numerous segments would be identified, and multiple reports produced for each segment, resulting in a vast amount of output information. However, even with this large quantity output, the SDSS still provides superior access to information when compared to traditional techniques. The user reports contain all essential information that would otherwise be contained in extensive manuals, without involving the inevitable frustration of sorting through the manuals. Additionally, instead of having only a single manual, the expert system contains knowledge from multiple expert sources. This format ensures that the user and subsequently all involved personnel are provided with accurate and complete solutions to the oil spill problem. Information can also be easily updated to include any new or changing information regarding both coastline characteristics and oil spill response knowledge.

An additional issue relating to the advice produced by the SDDS, concerns the lack of prioritization with regards to the order in which affected costal segments should be dealt with, and which specific response techniques should be implemented first. The system does provide the sensitivity values associated with each coastal section and does distinguish between recommended and optional techniques. However, advice presented by the SDSS, would be substantially improved if the output reports were organized using this specific information. Reports could be sorted based on environmental sensitivity values, in addition to the proximity of the coastal area to the oil spill. Furthermore, more information could be provided in the reports concerning the response priority levels, in addition to one or two specific response options which are best suited to the situation, as opposed to list of all relevant options.

Although the SDSS appears thorough and highly informative, it should be noted that it is not intended to be the exclusive means of decision-making in the event of an oil spill. As stated clearly in its title the system is meant for decision support not decision-making. In this capacity the system should function as a starting point for discussions and further decision-making. However, the solutions provided by the system are based on the standard response options provided by professional oil spill experts, and therefore are precise with regards to the techniques that can or cannot be used for specific types of coastline and coastal resources. Issues that may induce further discussion include political or monetary interests, which are often unpredictable factors. Of particular concern in the Labrador region is the opinion of local Aboriginal groups, which should be an essential component during the decision-making process.

A major benefit offered by SDSS development is the opportunity to explore and integrate varying views and use them to establish a standardized decision-making process. In the field, oil spill response proceedings are often decided by a single expert, based on prior experience, an authoritative understanding, and a rapid assessment of the situation. Such circumstances do not encourage a standardized approach to oil spill response. To some extent the lack of regulation is essential because each situation is unique and requires individual consideration. Conversely, many of the decisions that must be made during an oil spill response have solutions that are well established, and therefore can be consistently applied with effective results. For those decisions that are less straightforward, the expert system can still maintain a level of standardization through the use of preferences and biases, which permits a degree of leniency by providing alternate viable solutions. Additionally, the GIS, as part of the SDSS, encourages a degree of standardization, particularly in terms of coordinated data collection and sharing.

6.2 Conclusion

A Spatial Decision Support System (SDSS) is a means of overcoming the inherent problems of traditional oil spill response decision-making. Almost instantaneous access to data, knowledge, and advice will promote more efficient and subsequently more effective response proceedings. Eliminating the need for confusing response manuals and intensive on-site data collection will allow response personnel to focus on quickly implementing the necessary actions. The system will be particularly beneficial in the event that an oil spill response expert is not immediately available to determine the appropriate response techniques. If a response expert *is* available, the system is equally advantageous for providing decision support and data access directly to the expert.

Testing of the SDSS demonstrates a successful transfer of knowledge and data between the expert system and the GIS through the GUI medium. Spatial data is quickly identified and correctly modified to correspond to the input format for the expert system and its "action table" configuration. Results from the expert system are promptly returned to the GUI, and reorganized to present the user with a comprehensible display of response information. This integration of knowledge and spatial data promotes enhanced response times through improved data access capabilities and simplification of the otherwise complex and time-consuming tasks involved in oil spill response decision-making.

6.3 Future Research

The integration of expert systems and Geographic Information Systems (GIS) for oil spill response holds great potential for future research. As demonstrated by this study, a knowledge-based spatial decision support system (SDSS) can offer valuable support in the event of an oil spill, particularly with regards to improved data access, rapid availability of knowledge, and minimization of time-consuming tasks.

An immediate future prospect, with regards to this research, would be the completion of a fully-integrated SDSS, improving upon the prototype system. A fully-integrated structure would eliminate the need to extract data from the GIS and transfer it to the expert system. The ArcGIS, and ArcObjects development platform, available through ESRI would greatly facilitate this development owing to the much superior capabilities of ArcGIS for interaction with Visual Basic.

Incorporating an oil spill modeling environment would also enhance the SDSS, by providing more accurate simulations of oil spill behaviour. A more exact spill model would improve the process of identifying coastal areas at risk, which would subsequently improve the ability of spill response personnel to prepare response operations. The SDSS would also benefit from the collection of more detailed environmental data, including ocean current, tidal and bathymetric information. Due to ongoing developments in Anaktalak Bay associated with the Voisey's Bay project, it is likely that more detailed data will soon exist.

Response operations would also benefit from more rapid access to the required equipment, and better information regarding availability of equipment. The addition of an equipment database to the GIS would provide instant access to equipment inventories, and therefore enable response plans to be prepared with specific reference to availability equipment. The database could contain information pertaining to the type and number of equipment units, in addition to the exact location of each unit. The expert system would be able to reference the equipment database during the inference process in order to determine if the appropriate equipment is available to implement the recommended response procedures. If the required equipment is not available, the expert system could explore alternative solutions, and hence modify the output advice to avoid recommending techniques that under the circumstances can not be implemented, and instead take advantage of the resources that are available.

The advisory function of the expert system could also be used more extensively in the SDSS as an analytical tool. Expert systems have frequently been used in combination with GIS as means of educating the user about the analytical functions of the GIS and how they can be implemented (Openshaw, 1992). A second knowledge-base within the expert system, as demonstrated by Zhu *et al.* (1998), could contain expert knowledge relating to spatial analysis functions of the GIS, in order to guide the user in employing different types of models and analysis. This addition to the SDSS would promote greater user interaction, and allow the user to exhibit more control over the functions of the GIS.

The inclusion of traditional knowledge would likewise improve the reasoning capabilities of the expert system and subsequently the performance of the SDSS. The region of Labrador is home to several aboriginal groups, who possess important traditional ecological knowledge, which would be useful for determining appropriate oil spill response proceedings. All forms of traditional knowledge and values should be taken into account when considering options for oil spill response.

Finally, it would be beneficial for future oil spill response SDSS's to allow for the storage and retrieval of previous oil spill analysis results. Direct access to previous oil spill evaluations through the SDSS would enable response experts and personnel to reassess the value of the SDSS output and the success of the implemented response operations.

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Appendix A: SDSS Text Output

General Information Report – Spill Scenario # 1:

GENERAL INFORMATION:

DATE: June 3, 2003

LOCATION OF SPILL: 6254202 mN, 557960 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 10 minutes

SPEED OF OIL SLICK MOVEMENT: 0.179 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 96.556 degrees

TYPE OF OIL: Diesel (Fuel Oil No. 2)

Diesel is a light viscosity oil, and therefore will spread quickly. Diesel is a low to medium density oil and should be naturally removed from the ocean surface in less than a week. However, any pollution of coastal resources or features could persist, and treatment needs should be assessed.

API: 34.5
POUR POINT: -15
FLASH POINT: 180

VOLUME OF OIL SPILLED: 79.49 Cubic Meters

AFFECTED COASTLINE: 6 Coastal segments may become affected by the spill; 3 of these segments are directly in the path of the oil slick, while 3 of these segments are not within the direct path, but are located within 200 meters of the slick and therefore may be at risk.

WIND DIRECTION (Towards): 95 degrees

WIND SPEED: 5 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45

Segment # 109 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 109 is NOT in the direct path of the oil slick for the identified 10 hour time period.
However, if conditions change this coastal area may be at risk.

Segment # 109 is at an average distance of 5623.715 meters from the oil spill source, and measures 1367.257 in length; beginning at 6252718.25728 mN, 557689.21305 mE, and running to 6253580.30181 mN, 558678.26084 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Beach.

The ESI (Sensitivity) level for this segment is 6 (where 1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- NATURAL SINK
- SHOALS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 108 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 108 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 2 hour(s) of the initial spill. However, that time has already passed and it is likely that this coastal area has become affected. Shoreline Treatment is recommended.

Segment # 108 is at an average distance of 2930.349 meters from the oil spill source, and measures 742.5921 in length; beginning at 6253580.30181 mN, 558678.26084 mE, and running to 6253966.27325 mN, 559280.3311599999 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF
- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 107 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 107 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 2.33 hour(s) of the initial spill. However, this time will be up in less than 30 minutes, and will be difficult to organize a protection operation within the limited time period. Shoreline Treatment is recommended.

Segment # 107 is at an average distance of 2942.645 from the oil spill source, and measures 602.9349 mn length; beginning at 6253966.27325 mN, 559280.3311 mE, and running to 6253719.27353 mN, 559798.31036 mE.

This section of coastline is Bedrock, and the Primary Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 8 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF

The following EQUIPMENT may be required to minimize effects of the spill:

- Inshore Support Boats, for redirection, recovery and/or booming operations
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Water Heaters
- Manual Crew, for cleanup or treatment

Segment # 106 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 106 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 4 hour(s) of the initial spill. Shoreline Protection is recommended.

Segment # 106 is at an average distance of 3054.763 meters from the oil spill source, and measures 781.821 in length; beginning at 6253719.27353 mN, 559798.31036 mE, and running to 6253413.24582 mN, 560490.37583 mE.

This section of coastline is a Boulder-Beach, and the Primary Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 8 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Inshore Support Boats, for redirection, recovery and/or booming operations
- Geotextile Barriers
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Water Heaters
- Manual Crew, for cleanup or treatment

Segment # 105 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 105 is NOT in the direct path of the oil slick for the identified 10 hour time period.
However, if conditions change this coastal area may be at risk.

Segment # 105 is at an average distance of 5863.331 meters from the oil spill source, and measures 1371.2063 in length; beginning at 6253413.24582 mN, 560490.37583 mE, and running to 6253154.25853 mN, 561785.39391 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Beach

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- NATURAL SINK
- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 104 Summary Report – Spill Scenario # 1:

COASTAL SEGMENT REPORT:

Segment # 104 is NOT in the direct path of the oil slick for the identified 10 hour time period.
However, if conditions change this coastal area may be at risk.

Segment # 104 is at an average distance of 20112.944 meters from the oil spill source, and measures 1771.7291 in length; beginning at 6251917.20033 mN, 562921.47337 mE, and running to 6253154.25853 mN, 561785.3939199999 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Beach.

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- ALGAE
- BARNACLES
- FUCUS

COASTAL FEATURES associated with this segment include:

- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 108 Shoreline Treatment Report – Spill Scenario # 1:

SHORELINE TREATMENT FOR
SEGMENT # 108 (6253580.30181 mN, 558678.26084 mE TO 6253966.27325 mN, 559280.3311 mE):
*To be carried out if the oil slick reaches the shoreline

Segment # 108 is at an average distance of 2930.349 meters from the oil spill source.
The oil slick will reach this segment within approximately 2 hour(s) of the initial spill.

SHORELINE TREATMENT STRATEGIES:
(i.e. actions that should be taken if the shoreline segment comes in contact with the oil slick)

- Minimize waste generation using in-situ techniques
- Manual techniques are preferred

RECOMMENDED SHORELINE TREATMENT OPTIONS:
(i.e. the best treatment options for dealing with a shoreline segment that has come into contact with the oil slick)

- Natural Recovery

Natural Recovery means allowing the oil to recover naturally, and should always be considered the preferred option.

It is generally necessary to monitor the location to ensure that the assessment is correct or that conditions do not change.

This technique is implemented when:

(a) the cleaning options have the potential to cause more damage than they prevent,

(b) response techniques will not accelerate natural recovery or,

(c) response operations could place cleanup personnel in danger.

- Mechanical Recovery is recommended BUT this segment of the coast is not suited to machinery. Alternative methods should be explored.

OPTIONAL SHORELINE TREATMENT OPTIONS:
- Flooding
- Low-Pressure Cold-Water Wash
- Vacuum Recovery
- Vegetation removal and/or cropping
- Dispersants
- Shoreline Cleaners
- Solidifiers
- Bioremediation

Segment # 107 Shoreline Treatment Report – Spill Scenario # 1:

SHORELINE TREATMENT FOR
SEGMENT # 107 (6253966.27325 mN, 559280.33115 mE TO 6253719.27353 mN, 559798.31036 mE):
*To be carried out if the oil slick reaches the shoreline

Segment # 107 is at an average distance of 2942.645 meters from the oil spill source.
The oil slick will reach this segment within approximately 2.33 hour(s) of the initial spill.

RECOMMENDED SHORELINE TREATMENT OPTIONS:
(i.e. the best treatment options for dealing with a shoreline segment that has come into contact with the oil slick)

- Natural Recovery
  Natural Recovery means allowing the oil to recover naturally, and should always be considered the preferred option.
  It is generally necessary to monitor the location to ensure that the assessment is correct or that conditions do not change.
  This technique is implemented when:
  (a) the cleaning options have the potential to cause more damage than they prevent,
  (b) response techniques will not accelerate natural recovery or,
  (c) response operations could place cleanup personnel in danger.

- Low-Pressure Cold-Water Wash
  Low-Pressure, Cold Water Wash is used to flush oils at low pressure, using normal temperature water, towards a collection area. Output pressure from the hose should be less than 3 bars (50 psi) and are controlled by a nozzle.
  Booms or other methods of trapping and containment are used to collect the oil.

OPTIONAL SHORELINE TREATMENT OPTIONS:
- Flooding
- Low-Pressure Warm-Water Wash
- High-Pressure Cold-Water Wash
- Vacuum Recovery
- Vegetation removal and/or cropping
- Dispersants
- Shoreline Cleaners
- Solidifiers
- Bioremediation

RECOMMENDED SHORELINE TREATMENT OPTIONS FOR SMALL AMOUNTS OF OIL ONLY:
- Manual Removal
- Passive Sorbents

Segment # 106 Shoreline Protection Report – Spill Scenario # 1:

SHORELINE PROTECTION
FOR SEGMENT # 106 (6253719.27353 mN, 559798.31036 mE TO 6253413.24582 mN, 560490.37583 mE):

Segment # 106 is at an average distance of 3054.763 meters from the oil spill source.
The oil slick will reach this segment within approximately 10 hour(s) of the initial spill.

RECOMMENDED SHORELINE PROTECTION OPTIONS:
(i.e. Methods used to prevent the oil slick from reaching the shoreline)

- Nearshore redirection of oil away from the segment is used when the shoreline substrate is sensitive to retention.

Redirection can be used to divert oil away from a resource at risk

Redirection is accomplished through deployment of booms or other barriers.

This technique is often used where current speeds or breaking waves would make exclusion booming difficult, or where there is not enough booming equipment available

Boom configuration will depend on the size of the slick, the amount of redirection necessary, and flow conditions (currents) in the area. Boom configurations include:

(a) Single
(b) Cascading
(c) Chevron
(d) Open chevron

It is easier to deal several shorter booms in a staggered or cascading formation, than with one long boom. The deployment angle of the boom will depend on the current speed.

OPTIONAL SHORELINE PROTECTION OPTION:

- Exclusion Booming

Exclusion Booming is used to "exclude" oil from a certain location, such as a shoreline, pocket beach, lagoon, river mouth, etc.

The boom extends above and below the water surface, to prevent the oil from escaping.

- Contact Barriers

Contact Barriers prevent contact between the oil and the resources or shoreline. Barriers can be created by placing a physical barrier or cover over the shoreline. This technique is particularly effective in preventing oil from coating the upper intertidal area, where cleanup can become difficult.

Physical and Textile barriers can include plastic sheeting, a geotextile, or sorbent material. These barriers are held down using stakes, sand bags, cobbles, or other weights. Commonly used barriers include:

General Information Report – Spill Scenario # 2:

GENERAL INFORMATION:

DATE: September 23, 2003

LOCATION OF SPILL: 6254202 mN, 557960 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 15 minutes

SPEED OF OIL SLICK MOVEMENT: 0.259 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 273.445 degrees

TYPE OF OIL: Diesel (Fuel Oil No. 2)

Diesel is a light viscosity oil, and therefore will spread quickly. Diesel is a low to medium density oil and should be naturally removed from the ocean surface in less than a week. However, any pollution of coastal resources or features could persist, and treatment needs should be assessed.

API: 34.5
POUR POINT: -15
FLASH POINT: 180

VOLUME OF OIL SPILLED: 79.49 Cubic Meters

AFFECTED COASTLINE: 8 Coastal segments may become affected by the spill; 7 of these segments are directly in the path of the oil slick, while 1 of these segments are not within the direct path, but are located within 200 meters of the slick and therefore may be at risk.

WIND DIRECTION (Towards): 275 degrees

WIND SPEED: 8 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45

Segment # 109 Summary Report – Spill Scenario # 2:

COASTAL SEGMENT REPORT:

Segment # 119 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 5.67 hour(s) of the initial spill.
Shoreline Protection is recommended.

Segment # 119 is at an average distance of 7777.954 meters from the oil spill source, and measures 482.1928 in length; beginning at 6254943.23439 mN, 553797.11682 mE, and running to 6254708.25222 mN, 554140.1192 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- ALGAE
- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF
- SHOALS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 118 Summary Report – Spill Scenario # 2:

COASTAL SEGMENT REPORT:

Segment # 118 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 4.67 hour(s) of the initial spill.
Shoreline Protection is recommended.

Segment # 118 is at an average distance of 3751.129 meters from the oil spill source, and measures 361.0738 in length; beginning at 6254708.25222 mN, 554140.1192 mE, and running to 6254542.26601 mN, 554401.10018 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Beach.

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- ESTUARY
- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 116 Summary Report – Spill Scenario # 2:

COASTAL SEGMENT REPORT:

Segment # 116 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 4 hour(s) of the initial spill. Shoreline Protection is recommended.

Segment # 116 is at an average distance of 3131.971 meters from the oil spill source, and measures 372.5554 in length; beginning at 6254492.25619 mN, 554728.09738 mE, and running to 6254234.2587 mN, 554921.10785 mE.

This section of coastline is a Boulder-Beach, and the Primary Supratidal Form (Backshore) is a Cliff.

The ESI (Sensitivity) level for this segment is 8 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- BACKSHORE CLIFF
- SHOALS

The following EQUIPMENT may be required to minimize effects of the spill:

- Inshore Support Boats, for redirection, recovery and/or booming operations
- Geotextile Barriers
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Water Heaters
- Manual Crew, for cleanup or treatment

General Information Report – Spill Scenario # 3:

GENERAL INFORMATION:

DATE: September 23, 2003

LOCATION OF SPILL: 6256203 mN, 564183 mE

TIME OF SPILL (24Hrs): 20:00

TIME ELAPSED SINCE SPILL: 2 hours, 10 minutes

SPEED OF OIL SLICK MOVEMENT: 0.205 knots

BEARING OF OIL SLICK MOVEMENT (Towards): 96.55 degrees

TYPE OF OIL: Fuel-Oil-No.-4

Fuel Oil No. 4 is a medium viscosity oil and therefore will spread fairly quickly. Fuel Oil No. 4 is a medium to high density oil and could persist in the environment for months; protection, treatment and/or cleanup may be necessary.

API: UNKNOWN
POUR POINT: -3
FLASH POINT: 78

VOLUME OF OIL SPILLED: 3.97 Cubic Meters

AFFECTED COASTLINE: 4 Coastal segment(s) may become affected by the spill; 1 of these segments are/is directly in the path of the oil slick, while 3 of these segments are not within the direct path, but are located within 200 meters of the slick and therefore may be at risk.

WIND DIRECTION (Towards): 95 degrees

WIND SPEED: 6 knots

OCEAN CURRENT BEARING: 158 degrees

OCEAN CURRENT SPEED: 0.097 knots

SEA SURFACE TEMPERATURE (Degrees Celsius): 2.45

Segment # 157 Summary Report – Spill Scenario # 3:

COASTAL SEGMENT REPORT:

Segment # 157 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 9.33 hour(s) of the initial spill. However, that time has already passed and it is likely that this coastal area has become affected. Shoreline Treatment is recommended.

Segment # 157 is at an average distance of 12798.132 meters from the oil spill source, and measures 884.2321 in length; beginning at 6255444.28241 mN, 569728.69819 mE, and running to 6255992.26087 mN, 569343.71621 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Wetland.

The ESI (Sensitivity) level for this segment is 6 (1 is low sensitivity, 10 is high sensitivity).

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 157 Shoreline Protection Report – Spill Scenario # 3:

SHORELINE PROTECTION
FOR SEGMENT # 157
(6255444.282410001 mN, 569728.69819 mE TO 6255992.26087 mN, 569343.71621 mE):

Segment # 157 is at an average distance of 12798.132 meters from the oil spill source.
The oil slick will reach this segment within approximately 11 hour(s) of the initial spill.

SHORELINE PROTECTION OBJECTIVES:
(i.e. goals that should be met in order to prevent the oil slick from reaching the shoreline segment)

RECOMMENDED SHORELINE PROTECTION OPTIONS:
(i.e. Methods used to prevent the oil slick from reaching the shoreline)

- Nearshore redirection of oil towards the segment is used when the substrate is not sensitive to oil retention. Redirection can be used to divert oil away from a resource at risk

Redirection is accomplished through deployment of booms or other barriers.

This technique is often used where current speeds or breaking waves would make exclusion booming difficult, or where there is not enough booming equipment available for exclusion booming strategies.

Boom configuration will depend on the size of the slick, the amount of redirection necessary, and flow conditions (currents) in the area. Boom configurations include:

(a) Single
(b) Cascading
(c) Chevron
(d) Open chevron

It is easier to deal several shorter booms in a staggered or cascading formation, than with one long boom. The deployment angle of the boom will depend on the current speed.

* The presence of boulders or shoals may make it difficult to access the shore from the water, and may also make it difficult to deploy booms in the area.

- Shoreline Booms or Barriers
OPTIONAL SHORELINE PROTECTION OPTION:

- Exclusion Booming

Exclusion Booming is used to "exclude" oil from a certain location, such as a shoreline, pocket beach, lagoon, river mouth, etc.

The boom extends above and below the water surface, to prevent the oil from escaping.

- Shoreline Protection Booming
- Shoreline Boom or Barriers

Segment # 157 Summary Report – Spill Scenario #4:

Segment #157 will be affected by the oil within the identified 10 hour time period.
Warning:
It was estimated by the GIS that the oil slick would reach this segment in 2.33 hour(s) of the initial spill. However, that time has already passed and it is likely that this coastal area has become affected. Shoreline Treatment is recommended.

Segment # 157 is at an average distance of 5312.047 meters from the oil spill source, and measures 884.2321 in length; beginning at 6255444.28241 mN, 569728.69819 mE, and running to 6255992.26087 mN, 569343.71621 mE.

This section of coastline is a Sand/Gravel-Beach, and the Primary Supratidal Form (Backshore) is a Wetland

FLORAL AND FAUNAL RESOURCES associated with this segment, which could be damaged by the oil, include:

- FUCUS

COASTAL FEATURES associated with this segment include:

- SHOALS
- TIDAL POOLS

The following EQUIPMENT may be required to minimize effects of the spill:

- Sheltered Water Boom, for redirection and recovery of oil
- Inshore Support Boats, for redirection, recovery and/or booming operations
- Intertidal or Shoreline Boom
- Skimmers or other oil recovery equipment
- Personnel for deployment or recovery activities
- Earthmoving Machinery
- Temporary Liquid Storage or Transfer Equipment
- Debris Storage and/or Transfer Equipment
- Water Pumps, Hoses, etc
- Manual Crew, for cleanup or treatment
- Agricultural Machinery
- Temporary Oily Solid Waster Storage and/or Transfer Equipment

Segment # 157 Shoreline Treatment Report – Spill Scenario # 4:

SHORELINE TREATMENT FOR
SEGMENT # 157 (6255444.28241 mN, 569728.69819 mE TO 6255992.26087 mN, 569343.71621 mE):
*To be carried out if the oil slick reaches the shoreline

Segment # 157 is at an average distance of 5312.047 meters from the oil spill source.
The oil slick will reach this segment within approximately 2.33 hour(s) of the initial spill.

SHORELINE TREATMENT OBJECTIVES:
(ie. the goals for an effective shoreline clean-up operation)

- Minimize operational damage to dune, marsh or peat bog areas

SHORELINE TREATMENT STRATEGIES:
(ie. actions that should be taken if the shoreline segment comes in contact with the oil slick)

- Minimize waste generation using in-situ techniques
- Manual techniques are preferred

RECOMMENDED SHORELINE TREATMENT OPTIONS:
(ie. the best treatment options for dealing with a shoreline segment that has come into contact with the oil slick)

- Natural Recovery

  Natural Recovery means allowing the oil to recover naturally, and should always be considered the preferred option.
  It is generally necessary to monitor the location to ensure that the assessment is correct or that conditions do not change.
  This technique is implemented when:
  (a) the cleaning options have the potential to cause more damage than they prevent,
  (b) response techniques will not accelerate natural recovery or,
  (c) response operations could place cleanup personnel in danger.

- Mechanical Recovery

  Mechanical Removal uses mechanical equipment to remove oil and oiled materials. Each type of equipment has a particular application:
  - Scrapers and graders can operate only on hard and relatively flat surfaces and are capable of moving only a thin cut (~10 cm) of surface material.
  - Loaders, bulldozers and backhoes can operate in a wider range of conditions and are designed to dig and remove large volumes of material. * Front-end loaders are the preferred type of equipment for this type of shoreline because of generally poor traction. Backhoes are an alternative choice.

- Backhoes, draglines and clamshells use an extending arm or crane so that they may be operated from a barge or from a backshore area and can reach to pick up material.

- Beach cleaning machines can operate either directly on a beach or off-site to treat oiled sediments.

- Vacuum trucks remove pooled oil or oil collected in sumps.

Test runs or trials with experienced equipment operator will determine which machines are best suited.

The selection of equipment will also depend on the objective of the cleanup operations, which should be discussed prior to implementation. Excessive removal of coarse sediment should be avoided, as natural replacement rates are very slow.

OPTIONAL SHORELINE TREATMENT OPTIONS:
- Flooding
- Low-Pressure Cold-Water Wash
- Vacuum Recovery
- Vegetation removal and/or cropping
- Dispersants
- Shoreline Cleaners
- Solidifiers
- Bioremediation

RECOMMENDED SHORELINE TREATMENT OPTIONS FOR SMALL AMOUNTS OF OIL ONLY:
- Manual Removal
- Passive Sorbents
- Tilling/Aeration
- Surf Washing or Sediment Reworking