Environmental Constraints Analysis for Granular Resources Development in the Beaufort Sea

A New Methodology Using Low Cost Raster GIS

Earth & Ocean Research Ltd.

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Introduction

In Northern Canada, including offshore areas adjacent to the Northwest Territories and Yukon, management of most construction material resources is the responsibility of the Department of Indian and Northern Affairs and Northern Development. Granular construction materials are relatively scarce in the offshore area in the Beaufort Sea. The dredging of sand and gravel deposits from the sea bed in this region has proven to be cost effective in the construction of artificial islands which are used as temporary drilling structures during hydrocarbon exploration. Since about 1970, approximately 40 million cubic metres of granular material has been dredged from the ocean floor to create artificial islands or caisson-supported berms. Future construction of hydrocarbon production facilities in the Beaufort Sea region will create a much greater demand for seabed materials, estimated to be of the order of 700 million cubic metres of sand and gravel.

A significant amount of environmental information has been collected for the Beaufort Sea, and specific studies have addressed the impacts of dredging operations, including the impacts of dredging and overburden disposal. In consideration of the large sediment loads carried to the sea by the Mackenzie River, activities such as marine dredging are generally considered to have limited, long-term impact on the Beaufort Sea environment. Other studies have focussed on the potential environmental impact of oil spills in the Beaufort Sea. Compilations of shoreline sensitivity maps and offshore sensitivity regional maps have pointed out a growing number of potential limitations of the activities required for granular resource development. New environmental data for the Beaufort Sea include such things as estimates of biological resources at risk, amounts of human activity in different areas, and the behavior of oil in the arctic shoreline environment. It is now possible to plan a pipeline route from an offshore area such as Amauligak J-22 to Richards Island, taking into account not only the physical characteristics of the pipeline corridor itself (seabed slope, sediment type, etc.), but also the environmental 'cost' of bringing oil ashore at different localities. Such environmental constraints also take into account such things as the direct impact of dredging on the marine benthic environment, including mortality levels of different species and the destruction of natural habitats.

This study investigates the applicability and suitability of low-cost, raster GIS analysis to carry out environmental constraints analysis in support of granular resource development in the marine environment as described above. The purpose of this pilot study is to develop and demonstrate a methodology that can be used to evaluate and incorporate different constraints that might be subject to changing conditions.

This report consists of three tests which demonstrate both the broad range of mapping capabilities of a low cost raster GIS for environmental constraints analysis, plus the specific analytical procedures required for visualization of spatial data. Test

1 provides a method for evaluating the direct impact of marine dredging on the benthic environment at the ERKSAK borrow site in the Beaufort Sea. Test 2 illustrates a method for selecting a pipeline corridor from the Amauligak J-22 offshore discovery area to the Richard's Island by minimizing the environmental 'cost' based on shoreline sensitivity data from the Environmental Atlas for Beaufort Sea Oil Spill Response. Test 3 provides a regional perspective for planning marine surveys in support of granular resource development including the preparation of a regional digital terrain model for the Beaufort Sea bathymetry, the construction of depth profiles along potential pipeline corridors, and the visualization and analysis of changing ice conditions and how this data can be used to assist planning for field surveys.

This report is largely pictorial, and considerable effort has gone into preserving a high level of fidelity in the final maps and figures. Black and white, page size hard copy proved unsatisfactory for visualizing the informative but oftentimes complex composition of detailed raster images. Another factor that mitigated against black and white map production was the relatively large number of figures produced in this report (eighty two), the reproduction of which would have added considerably to the bulk and ease of deliverability of the final report.

Instead of black and white page size figures, it was decided to present the final map images in an *electronic format*, which serves as a companion electronic document to the hard copy report. A custom program was created, SHOW.SPR, which allows viewing of figures to either in sequential order on a numeric basis. As PCX files, these figures can also be viewed with standard graphics programs such as WINDOWS PCPAINT, PAINTBRUSH, or Corel Draw, but the colour palettes will probably change with each system and images may take on different appearances for different packages.

Figures 1 to 82 are located on 'DISKS 1and 2', on 3.5 inch diskette in standard, in DOS format after compression by PKZIP. These files can be examined using inFOcus. If you have inFOcus and would like to prepare the figures for viewing, please carry out the following steps:

1. Make a new directory on your hard drive called c:\raster\pcx

2. Copy all of the files from DISK 1 and 2 into the above directory, which should then contain PCXFILE1.zip, PCXFILE2.zip, and PKUNZIP.exe

3. Check to make sure that inFOcus is loaded on your hard drive (either 'c:\infocus' or 'c:\infohome' n most machines) and that inFOcus is included in the PATH command in the AUTOEXEC.BAT file.

4. Unzip the PCX files by typing PKUNZIP PCXFILE1 followed by PKUNZIP PCXFILE2

5. Check to make sure that the following files are located in c:\raster\pcx

SLIDES.DBF	(contains the names of PCX files in sequential viewing order)
SLIDES.CDX	(index file for above)
SHOW.SPR	(FOXPRO program file)
SHOW.SPX	(FOXPRO program file)
FOXR.EXE	(FOXPRO program file)

6. Modify the AUTOEXEC.bat to include the new directory path c:\raster\pcx

To view the figures, go to the c:\raster\pcx directory and type the following command:

```
foxr show.spr
```

The electronic document is intended as a companion document to the final report. On occasion, the reader may also be requested to run the raster GIS software "IDRISI" *(not provided)* directly in order to visualize certain map sequences. Therefore, please make sure that IDRISI has been loaded on the hard drive as well.

Test 1
A Method for Evaluating the Direct Impact of Marine Dredging on the Benthic Environment in the Beaufort Sea

Background

The removal of seabed material by dredging has a direct impact on both the benthic biota and the benthic habitat. Such changes can be visualized and analyzed in a quantitative manner using a geographic information system. This is especially true for benthic organisms, which, unlike other species in the marine ecosystem such as anadramous fish or migratory bird populations, are characterized by a fair degree of spatial and temporal continuity. The direct and measurable effects of marine dredging include:

- reduction of total biomass in the area of excavation
- the creation of spatial discontinuities in the benthic environment
- the induction of temporal changes in the benthic community owing to recolonization

Any analysis of the effects of dredging in the marine environment should take into account the disruptions caused to both the ***benthic community*** (invertebrates and microalgae) and the ***habitat*** (primarily the surface sediments) in which these communities live.

The analysis of the *biological effects* of dredging should attempt to quantify such things as:

- the amount of species mortality and physical damage that occurs during excavation or overburden stripping,
- the amount of smothering that occurs, either adjacent to the excavation area or in areas where unsuitable dredge material brought to the surface has been rejected and dumped back on the seabed by the dredge operator.

The analysis of dredging impact on *benthic habitats* should take into account such things as:

- the degree of removal or mechanical disruption of the surficial sediments, particularly those most suitable for supporting benthic communities
- the amount of suspension and redistribution of fine sediments, either by turbulence caused by the dredge or leakage from the dredge as it moves through the water column toward the surface
- any changes in sedimentation rates, water quality or turbidity that persists after the dredging operation has been completed.

If such information were available to DIAND, either from field studies or modelling carried out by the scientific community, is there a simple and inexpensive manner in which the these results can be incorporated into the overall planning process for the recovery of borrow material from the sea floor? Can the results be analyzed and visualized in map form in a manner consistent with current desktop mapping capabilities at DIAND?

Test 1 demonstrates a methodology for visualizing information that describes the direct impact that dredging has on the benthic environment for a theoretical excavation area at the ERKSAK borrow site in the Beaufort Sea.

The analytical tool used in this investigation is a low-cost ($250), raster image processing system called IDRISI. A translator has been written to allow the free exchange of data ***in native formats*** between IDRISI and QUIKMap/inFOcus, the latter of which is used for desktop mapping and graphical inventories for a large amount of the granular resource spatial and attribute data for the Beaufort Sea at DIAND.

The Physiography of the ERKSAK Borrow Site

The study area for this test is the north central portion of the ERKSAK borrow site located off the Tuktoyuktuk Peninsula in the Beaufort Sea (Figure 1).

A bathymetry map can bean important ingredient in environmental investigations of benthic communities as discussed below. First, a bathymetry map provides a visual point of reference for planning and mapping results. Second, water depth can have a strong influence on other variables such surface sediment composition and the nature and composition of the benthic communities living in the area. It is important to have a good understanding of how bathymetric data can be used in environmental constraints analysis for marine dredging.

Figure 2 shows the physiography for the north central part of the ERKSAK borrow site. What follows is a step-by-step explanation of the process by which Figure 2 and other types of physiographic images for the ERKSAK borrow site were created. (The names of IDRISI modules are capitalized and shown in italics).

1. The source data for the ERKSAK bathymetry was a QUIKMap basemap file (Figure 3). Under normal circumstances, the QUIKMap/IDRISI translator would be used to convert this QUIKMap basemap directly to IDRISI format. However, the original bathymetry map was created circa 1983 with an early version of AUTOCAD. The QUIKMap basemap data set was found to be largely unstructured and difficult to translate into the IDRISI format. Thus, a new bathymetry data set was created in QUIKMap database format by tracing individual contour lines in the basemap file into polylines and polygons. The identifier (key) for each contour was its water depth. Although this process of digitizing was somewhat tedious, it provided a satisfactory digital data set for subsequent rasterization and modelling.

2. The area of interest at ERKSAK was defined with a QUIKMap polygon (Figure 3). This sub area was chosen because raster contour lines in an IDRISI image must extend to, and preferably cross, the outer boundary of the raster image. If contour lines don't extend to the edge of the raster image, any attempt to create a Digital Elevation Model (DEM) from the data will produce erroneous results It is also important that no 'dangling' bathymetry contours exist in the source elevation data. In the case of ERKSAK, discontinuities along bathymetry contours were not uncommon in the source data, especially in steep areas where contour lines were truncated for aesthetic reasons, i.e., to avoid over-crowding of contour lines. To summarize, two requirements must be met before conversion of bathymetry data from vector to raster format, namely: 1) the contours lines ***must*** extend to the edge of the final raster image area, and, 2) there can be no discontinuities along original vector contour lines.

3. After the QUIKMap basemap contour lines were traced into lines and polygons, the data was then translated into IDRISI vector file format using a custom IDRISI/QUIKMap translator module. This translation requires two steps; first for polylines, and second for polygons.

4. A 'blank' master image was created for the ERKSAK study area using the IDRISI data management function called *INITIAL*. This raster image contains no geo-referenced attribute data such as water depths or sediment types. However, its associated documentation file describes such things as image boundary locations, the type of data contained in the image document (real, integer, byte), the image title, and other data specifications. The master image for ERKSAK measured 500 pixels across and 400 pixels down. Next, a new working image was created for modelling bathymetry data using boundary and other definitions from the master image.

5. The next objective was to produce a raster ***contour*** image that could be used to generate a digital elevation model (DEM) for ERKSAK. The above IDRISI vector contour files were converted to raster format using the function *LINERAS*. Again, this is a two step process; one for converting polylines and the other for polygons. However, in the second step, contrary to what one might expect, polygons are not rasterized with the *POLYRAS* module in IDRISI. Instead, polygons are also rasterized with *LINERAS* to generate only the outer contour boundary of polygon areas. The output from LINERAS is given in Figure 4, a raster contour map similar in appearance to a vector contour map except for the 'stair-like' character of the contours which now exist in raster (pixel) format.

6. After rasterization, the map data was processed using *INTERCON*, a module that creates a digital elevation model (DEM) from raster contour data. Unlike the original contour image in Figure 4, all of the pixels in

the resulting image are assigned elevations, thereby providing a continuous surface which mimics the sea bottom at ERKSAK. At this stage, any errors or omissions in the source data are highly visible in the DEM image. Most commonly, errors show up in the form of dramatic angular or star-like patterns which obviously do not represent reasonable variations in seabed topography (Figure 5). Breaks in the vector contour lines such as the one in the central lower part of Figure 5 always lead to errors in the DEM.

7. Even with good source data sets, it is not unusual for DEM's produced by *INTERCON* to contain angular irregularities introduced by the modelling algorithm. The degree of angularity depends upon a number of factors, including the complexity of the contour data and the number of pixels in the final image. As a rule of thumb, image quality is directly related to the number of contours. Large images, e.g., 500X500 vs. 100X100 , also tend to produce slightly flawed DEM's. As well, processing time for DEM production increases exponentially as the number of pixels increases. The DEM for ERKSAK required about 3 hours of processing time for the complete raster image using a 25 Mhz 486 with 4 Mbs of memory and disk caching capability. Experience shows that many of the defects inherent in a newly created DEM can be removed using *FILTER* and specifying a low-pass filter operation. *FILTER*, requires only a few minutes to run even on large files, and was used twice in succession to produce the final ERKSAK DEM.

8. At this stage, the DEM for ERKSAK bathymetry is viewable using a function called *COLOR* which provides a breakdown of elevation data over the entire study area (Figure 6). Another way of visualizing the DEM is using *ORTHO*, which creates a 3-dimensional orthographic image (a series of closely spaced, linear bathymetric profiles across the site). For most DEM's, the number of rows that must be displayed in an orthographic image is too great for quality presentation. By using a function called *CONTRACT*, images can be 'thinned' by specified amounts in both the X and Y directions. Figure 7 shows an orthographic image of the ERKSAK DEM after thinning by 2X in each direction with an orientation looking from SW to NE, a viewing angle of 70 degrees from the vertical, and a vertical exaggeration of 10X. Figure 8 shows a two dimensional image of the same data after application of analytical hill shading to bring out topographic relief.

9. Once a digital elevation model has been generated for an area, one can begin to visualize the relationship between entities such as surface sediment characteristics or variations in benthic populations as a function of water depths. To do this one must first identify the optimal viewing angles for visualizing such data (including both the vertical and the azimuthal or compass directions. No two sites are alike. Some require

low viewing angles while looking from the east, while other require nearly vertical view angles while looking from the north. The selection of the optimal view point is generally accomplished by trial and error, a process which can be quite time consuming, particularly if one uses the standard IDRISI menu system for accessing the data.

One way to speed up this view point selection process is to use the *COMMAND LINE* function provided by IDRISI which is explained below. Initially, most users access IDRISI through a series of graphic menus. This procedure tends to be very slow. However, IDRISI also has the added capability of being accessible by DOS-type command lines in which the user submits function calls from the IDRISI DOS prompt (c:\IDRISI>). This reduces the amount of time required for testing. For example, the command line for visualizing the ERKSAK bathymetry in orthographic mode is as follows:

```
ortho x erkbat5a 0
```

where,

ortho	the name of the IDRISI module
x	indicates that command line mode is being use
erkbat5a	name of the DEM image to display
0	time delay before exit ('0'=manual, '-1' = printer, else time in seconds)

Batch files can be created with an ASCII editor allowing a series of command lines to be submitted to IDRISI . Such procedures make it possible to examine a series of different images in rapid succession that showing, for example, different view angles or view azimuths without the requirement of having to submit them one at a time. An example of such a meta-progam is the batch file 'tiptop.bat' which can be used to examine the ERKSAK bathymetry from different view angles from a constant view azimuth looking due north and adjusting the vertical exaggeration in such a manner as to keep terrain features at approximately the same height on screen. Similarly, the batch file 'rotatop.bat' allows for the sequential viewing of ERKSAK from different azimuths for a constant view angle of 60 degrees. If you have IDRISI and it is loaded, run these batch files from the IDRISI command prompt and observe what happens.

10. Notice that the images produced using the above batch files were more aesthetically pleasing and visually informative than previous examples. This improvement in image quality is the result of three additional data characterizations supported by IDRISI.

After rasterization and filtering, the ERKSAK bathymetry DEM was subjected to analytical hill shading using *SURFACE*, which, in essence, determines the positions of shadows and bright spots for a specific angle of illumination across the DEM. All of the hill-shaded images in 'tiptop.bat' and 'rotatop.bat' were created using a sun angle of 30 degrees from vertical and an azimuth of 315 degrees relative to true north on the original DEM. The hill-shaded image was 'smoothed' using *FILTER* , specifying a low pass operation, to minimize angularity in the data.. Next, the data values in the hill-shade image were reclassified using the *RECLASS* to provide a colour image that could be draped over the elevation model to accentuate changes topography. The color image was created using a custom colour palette named 'sandwat2.pal' developed by the author which provides a 14-interval, gray/brown colour scale which ranges from black to light brown. The colour palette was created using the 'k' option in the *COLOR* module, which allows for the assignment of specific color definitions (% of red, green, blue) to specific data ranges in an image file. The images in tiptop and rotatop were created by draping the colour-coded, hill-shade image over the 3-dimensional physiographic image using *ORTHO* as per Figure 2, while varying the view angles and view azimuths using batch files.

One limitation of *ORTHO* is its inability to visualize images from any azimuth within a 360 degree perspective. For any particular image file, the view azimuths can only be varied within a range of 0 to 90 degrees. To rotate an image beyond 90 degrees one needs to create a new raster image by rotating the original up to 90 degrees clockwise or counter-clockwise using *TRANSPOS*. To rotate an image 180 degrees the image must be rotated twice by 90 degrees. Of course, in addition to the original DEM, any drape images or maps directly associated with this elevation model must also be rotated, otherwise the images will not overlay properly. Raster images that measure 500X400 pixels typically require 400-800kbytes of disk storage each. The amount of house-keeping and general overhead associated with maintaining such a multiplicity of data sets (not only the file management aspects but back up procedures for what are generally large files up to megabyte each) can be truly staggering. It is therefore important to plan in advance for the types and orientations of map images that are required for a project.

11. *PROFILE* can be used to show data values along transects across an image. For example, a profile can be constructed showing water depths along a pipeline corridor, where the output is an X-Y line graph showing depths in the Y direction and distance along track in the X direction.. Figure 9 shows a transect across ERKSAK generated using QUIKMap. Notice that the transect does not have to be straight. As in (3) above, the source database for this profile was a QUIKMap polyline which was translated to IDRISI vector format. The vector file was superimposed on

the ERKSAK bathymetry DEM using *PROFILE.* The output is given in Figure 10 which shows depth as a function of distance along track. Notice that in this case, the distance along track is given in degrees. This is because the reference coordinate system for the ERKSAK DEM was latitude/longitude. If the image had been referenced in metres, e.g., UTM coordinates, then the output from PROFILE would have been metres. Also, the depths for ERKSAK are not given in depths below sea level. Instead, depths are reported relative to a level of 50m below sea level (i.e, 50 metres minus the actual water depth). With IDRISI it is more convenient to deal with positive pixel values in a series of image files than negative values. Thus, a depth of 10m in QUIKMap corresponds to 40m in IDRISI; a depth of 30m in QUIKMap is 20m in IDRISI, and so on.

13. *PROFILE* may also be used to generate profiles of data over time as opposed to space. Using a 'mask' to define geographic areas of interest, PROFILE can monitor changes in data values in a time series of raster images (for example ice thickness as a function of month). Up to 15 polygon areas can be monitored simultaneously over a period of time. Each polygon is assigned an index number and an output is generated for each index number that includes summary statistics (mean, median, etc.) plus graphs where Y represents summary data values and X lists the temporal-based raster images in sequential order. This concept of using *PROFILE* for a time series analysis may be particularly well suited to environmental constraints analyses where temporal variations may be of greater significance than spatial variations in the data.

It possible to construct animated sequences by overlaying a series of raster images that depict spatial/temporal variations using the *COLOR* module and specifying 't' mode (for 'time' series). By way of example, the reader is asked to go to the main IDRISI directory (c:\IDIRISI) and, if you have IDRISI and it is loaded, do the following:

- type 'COLOR T' to start the image viewing system for time series
- type the file name 'ERKTOPO', which contains the list of related files
- enter '4' to select a user-defined colour palette
- type the palette name 'sandwat2'.

An animated sequence should now begin for the ERKSAK borrow site which shows the sea surface at an initial water depth of 36 m below present day sea level which rises at the rate of 3m per image until the borrow site is completely submerged by water (i.e., after 7 images have been shown). After watching this sequence of images a few times, one can begin to understand how the time series *COLOR* module operates

> and how the presentation quality might be improved. For example, the incremental change in seal level could be reduced from 3m to 1m per image, or, by increasing the view angle to 50 or 60 degrees from vertical to provide a better 'overview' of the sea level rise. Although the above time series focuses on sea level variations as a function of time at ERKSAK, a similar type of presentation could be created for showing environmental changes as a function of time as well.

As pointed out earlier, the construction of raster maps that depict sea bed topography will be an important aspect of many environmental constraints analyses. The above example has covered most of the methods and functions available in IDRISI associated with elevation models. The next section deals with a specific a environmental analysis associated with the direct impact of dredging on benthic communities for a hypothetical excavation project at ERKSAK.

Direct Impact of Dredging on Total Benthic Biomass

For this analysis it is assumed that a large oil and gas development project is about to begin in the Beaufort Sea which will require a staggering amount of borrow material for construction purposes. In the first phase of the project, there is a requirement to provide sedimentary material but virtually any type of sediment type will suffice, ranging from 100% gravel to 100% organic rich silt or mud, will suffice. The ERKSAK site has been chosen as the initial source of construction material owing to its relatively high grade of borrow material and proximity to the oil and gas development area. In Phase 1, it is hoped that a large amount of the organic rich surface sediments will be removed from the top of the seabed exposing high-grade gravel deposits for use later on. The initial plan calls for the excavation of a large pit measuring 2m deep by 10km by 20k across the north central part of ERKSAK. It is recognized that a good portion of the seabed in this area is blanketed by soft sediments.

Two concerns have emerged about the ecological impact of the removal of such a large amount of organic rich sediments at ERKSAK. First, it is unclear how the reduction of total biomass, (here measured in terms of total organic carbon) will effect the local ecosystem. Second, the reduction of total biomass may also effect the regional geology of the ERKSAK over the medium and long term.

The surficial geology at ERKSAK in the vicinity of the proposed pit is reasonably well known but fairly complex. The type of spatial analysis which follow could have carried out manually; but this would have been very tedious and unprecise. Figure 11 is a QUIKMap basemap that shows the location of 'Proven' and 'Prospective' borrow deposits are ERKSAK and Figure 12 shows the thickness of organic rich, fine-grained surface sediments. Figure 13 also shows the location of the proposed excavation pit which was created initially as a QUIKMap database polygon. The pit itself crosses areas characterized by complex geologic conditions in which the thickness of soft surface sediment types can vary between zero metres to areas where soft surface sediments can achieve thicknesses of 3metres or more.

Raster GIS Analysis

Objectives of the Raster Analysis.

- Prepare orthographic images depicting the physiography of the excavation before and after dredging

- Determine the loss of total organic carbon from the excavation area, taking into account the different concentrations of organic material in the soft sediments vs. borrow material plus the variable thickness of soft sediments.

The following steps were carried out to achieve the above objectives.

3-D Image Construction.

1. A new working raster image for surface sediments was created with *INITIAL* using identical boundary locations for the ERKSAK bathymetry image obtained from the blank master image of ERKSAK.

2. The contours for the ERKSAK surfaces sediment thickness in QUIKMap basemap were traced into a QUIKMap database and converted to IDRISI vector files for polylines and polygons using the QUIKMap/IDRISI translator.

3. The IDRISI vector lines were rasterized with LINERAS to produce a raster contour image (Figure 14).

4. This time, instead of producing a full-blown DEM for organic surface sediment thickness using *INTERCON*, a much quicker method was developed to provide full coverage away from contour lines in the raster image. The raster contour image was processed with a module called *DISTANCE* which calculates Euclidean distances (as the crow flies) between each cell in an image and the nearest set of map features. In this case, all map features were simple contours with identifiers equal to their depth. Distances were output in reference system units, which for ERKSAK was latitude/longitude, i.e., degrees, not metres. (Figure 15). Distance calculations were performed in a matter of minutes. Finally, *ALLOCATE* was used to assign each cell in the image the value of the depth of the closest contour line. This resulted in a stepped surface with the original contours located at the centre of each step (Figure 16). On files measuring of the order of 500X400 pixels, *ALLOCATE* required about 15 minutes for processing vs. two to three hours with *INTERCON.*

The positional errors with this method are minimized to a level of one half the contour interval, a precision acceptable in many analyses. More importantly, the stepped surfaces produced by *DISTANCE* are generally reasonable in appearance where as the output from digital elevation modelling is considerably less predictable.

5. Finally, the stepped contour image for surface sediment thickness was thinned by a factor of 2 in both X and Y directions, and a custom colour palette was created for visualizing the final results (Figure 17).

6. Next, an image was required for draping the surface sediments over the seabed. The original DEM for ERKSAK bathymetry was thinned by a factor of 4 in both X and Y directions to reduce disk storage space requirements and to minimize viewing times and data conversions. For the purposes of map overlays, the DEM was re-processed using *RECLASS* to convert the data type from real numbers to integers. A total of 19, 1 metre depth intervals were created. The original surface sediment distribution map was also thinned by 4X.

7. The location for the excavation area, initially created as a QUIKMap polygon, was exported to an IDRISI vector file and rasterized as described above. A color mask was created for the enhancing the contrast between surface sediments and the excavation area. The final images of the excavation are given in Figures 18,19 and 20, which illustrate the appearance of seabed before and after excavation, this time looking from SE to NW.

Impact of Dredging on Benthic Environment

The main objective here was to obtain the reduction in total organic carbon, which was inferred from calculations of the volume of organic rich sediments that were to be removed from the top of the seabed to a depth of 2m. The amount of total organic carbon in gravel was assumed to be 0.5% by weight (0.0125g grams per cubic cm), and soft sediments 2% by weight (0.05 grams per cubic cm), also assuming an approximate density for both sediment types of 2.5 g per cubic cm. The final objective was to obtain the total volume of each sediment type encountered and multiply this volume times the assumed level of total carbon contained in each sediment to obtain the total organic carbon removed by dredging. The steps required to perform this analysis are given below.

1. The first step was to isolate the soft sediments from the excavation area from the rest of the site using a method called map algebra. The IDRISI image containing the excavation site polygon is referred to as a binary image, i.e., it contained only two classes of pixels values (Figure 21). Those pixels with a value of '1' indicate the location of the excavation area; all other pixels contain 'zero's. Since the raster image for soft

sediments at ERKSAK contains positive values for all pixels where soft sediments exist, (either '1','2', or '3'), multiplying the excavation image by the soft sediment image produces positive values only for the area covered by the excavation pit plus soft sediments thereby isolating the sedimentary units in question; all other pixels become a 'zero' (Figure 22).

2. Recall that the original sediment thicknesses were artificially adjusted to avoid the problem of dealing with negative numbers in IDRISI. The adjustment included adding 10 m to all sediment thickness measurements, i.e., 0 m became 10 m, 1 metre became 11, etc. The sediment image was readjusted to indicate real thicknesses with the function *SCALAR* which allows for the application of standard numerical operations (multiply, divide, etc.) to whole images.

3. Since the dredge depth was to be 2 m, and the maximum thickness of soft sediments was 3 m, the class intervals in the sediments image had to be further adjusted using *RECLASS*. Dredging 2m of soft sediments in areas of 3m thickness would still leave 1m of soft sediment on the sea bed. Figure 23 shows how areas characterized by a thickness greater than 2 to 3 m were classified as '2', and areas in the 0 to 1 m range were assigned a '1'. The remaining areas were classified as '0'. Gravel deposits were classified in a similar manner, assigning values of '0' to areas of soft sediments were 2 m or greater, '1' where soft sediments were 0 to 1 m thick, and 2 everywhere else (Figure 24).

4. Finally, to obtain the volume of sediment removed, the areas of four categories of sediment were required. These were obtained using the module called *AREA*.

Sediment Type	Thickness (metres)	Area (sq metres)	Volume (cubic metres)
Soft Sediments	1m	58572979	58572979
	2m	62594360	125188720
			193761690 total
Gravel	1m	58572979	58572979
	2m	100447743	200895485
			259468464 total

Using the above volume determinations, the total reduction of organic carbon (TC) was calculated as follows:

Organic Sediments

$TC_{OgSed} = 2.0\% \ X (2.5 g/cm^3) X (1 X 10^6 \ cm^3/m^3) X (1 \ metric \ ton/10^6 g) X (194 X 10^6 m^3)$

$= 9.6$ million metric tons TC

Gravel

$TC_{Gravel} = 0.5\% \ X (2.5 g/cm^3) X (1 X 10^6 \ cm^3/m^3) X (1 \ metric \ ton/10^6 g) X (259 X 10^6 m^3)$

$= 3.2$ million metric tons TC

$TC_{Total} = 3.2 + 9.6 = 12.8$ million metric tons TC

Test 2
Optimizing the Selection of Pipeline Corridors in Environmentally Sensitive Areas in the Beaufort Sea

Background

The development of oil and gas fields in the Canadian Beaufort Sea will require plans for the year round protection of environmentally sensitive areas in both coastal and offshore regions.

The Environmental Atlas for Beaufort Sea Oil Spill Response (Dickens et al., 1987) provides a comprehensive sensitivity ranking system for different geographic areas in the Beaufort Sea. Quantitative assessments are provided for different categories of environmental sensitivities, including Human Use, Biology, and Shore Zone and Marine Oil Residence. In turn, each of these broad categories are further broken down into more specific categories of sensitivity to oil spills.

For example, the Human Use category accounts for both past and present human use of land and marine resources, and is based on historical and recent information regarding resource harvesting, important archaeological and heritage sites, national and territorial parks, sanctuaries and reserves, and native land claims.

The category of Biological Sensitivity provides rankings for key resources such as birds, fish and marine and terrestrial mammals. The key criteria used here were:

1. the known sensitivity of a species to the effects of oil and its vulnerability to oil exposure,
2. the importance of a species to regional residents, scientists, government or the public; and
3. the status of a species, especially rare or endangered types

Detailed and comprehensive analyses were carried out on a species by species basis for virtually the entire Beaufort Sea, from the Alaska/Yukon boundary in the west to the Baillie Islands in the east.

Finally, different geographic areas of the Beaufort Sea were ranked in terms of sensitivities toward coastal and marine oil residence, and a large body of supporting evidence was compiled describing such things as physical shoreline characteristics, seasonal ice distribution, the occurrences of storm surges, and so on.

For the purpose of this investigation it is not important to review the details about how each shoreline or geographic area was ranked in terms of its environmental sensitivity. Suffice it to say that the sensitivity values assigned to each geographic area represents a distillation of a large amount of information derived from the physical, biological and social sciences.

More important to this study is the fact that environmental sensitivities were not only quantified but ***mapped*** along shorelines and regional offshore areas. One limitation of this treatment from a planning point of view is the fact that sensitivity values represent *in situ* conditions, which assumes, for example, that an oil spill has occurred and the shoreline in question has been contaminated . What the sensitivity ranking system does not take into account is the environmental risk or vulnerability of human and biological resources as a function of *distance* from a potential oil spill or other man made threat to the environment. A spill in the vicinity of Baillie Islands is less likely to affect resources in the Herschel Island area as opposed to the northeastern part of the Tuktoyuktak Peninsula.

The objective of Test 2 was to use raster GIS to select a pipeline route that would connect the Amauligak J-22 oil discovery area to a designated location on Richards Island which would minimize the exposure of human and biological resources to the presence of an oil pipeline, either during construction or operation. A methodology was developed for extrapolating (spatially) the sensitivity rankings from the above Atlas for individual sections of shorelines in the North Point area to nearshore and offshore areas. The results were visualized on orthographic sensitivity maps.

Analytical Approach

The Environmental Sensitivity Atlas described above contains continuous sensitivity values for sections along the shoreline in the Beaufort Sea. Any evaluation of the potential effects of hydrocarbon development on human and biological resources should include not only the values placed on the resource sensitivities at specific localities but also the proximity of these resources to the proposed regions of development.

For example, consider a pipeline route that is designed to come ashore along a stretch of coastline that has been designated 'low' sensitivity. If the shoreline on either side of this section of the coast is ranked 'high', then it may be prudent to look for another region that is less threatened by development, for example, where 'low' sensitivity areas are surrounded by moderate sensitive areas. To apply these sensitivity ranking schemes in a wider spatial context, it is necessary to use a GIS system to perform operations such as distance and buffer type operations.

The North Point Area is shown in QUIKMap format in Figure 25 and the area selected for raster imaging is positioned over Richards Island (hatched area). An example of shoreline sensitivity ranking is given in Figure 26, which shows a high sensitivity area in the vicinity in Tuktoyuktak marked as a red polyline. Figure 27 shows the distribution of oil discovery wells in the vicinity of North Point and a possible distribution scenario for pipelines leading away from the discovery areas.

The procedure for raster analysis in Test 2 is briefly summarized as follows:

1. Using QUIKMap, a geographic search was performed on the sensitivity database file and database records were tagged for the sections of coastline that fall within the North Point Study area. These records were categorized and exported to three QUIKMap databases; one for low, medium and high shoreline sensitivities. A new field called 'rank' was added to each database , and assigned the values of '23' for low sensitivity, '52' for medium and '82' for high, which correspond to actual averaged sensitivity values for each category for the North Point area. (Note, for a real application, each shoreline unit in the Environmental Atlas has its own sensitivity value. For demonstration purposes in this study, average sensitivity values have been used for each category of low, medium and high).
2. A new study area for North Point was initialized and shoreline sections for each sensitivity class were rasterized using *LINERAS.*
3. *DISTANCE* was used to determine the distances between each shoreline unit and the surrounding area The outputs from *DISTANCE* are given in Figures 28 to 30, for high, medium and low sensitivities, respectively.
4. It was assumed that the risk to any individual section of shoreline would decrease as a function of distance away from that feature. The distance maps given in Figures 28 to 30 were reclassified using *RECLASS* using the table below, which essentially decreases the sensitivity to a level of one half each time the distance from that feature doubles, starting with a distance of 0.025 degrees longitude at North Point. In other words, the sensitivity values assigned to pixels lying within 0.025 degrees of a feature were the same as the original feature (e.g., 23 for a shoreline segment with low sensitivity). For distances of 0.025 to 0.05 degrees away from a feature, the sensitivity was reduced by a factor of 0.8, and so on, as given in the table below.

Factor	Lower Range (Degrees)	Upper Range (Degrees)
1.000	0.000	0.025
0.800	0.025	0.050
0.400	0.050	0.100
0.200	0.100	0.200
0.100	0.200	0.400
0.050	0.400	0.800
0.025	0.800	1.000

Raster analysis lends itself quite nicely to these types of numerical computations, and there is virtually no limit to the type of distance functions that could be applied here. Figures 31 to 33 show the results of reclassification of the original distance images for the above seven ranges.

5. Finally, the distance images from Figures 31 to 33 were added together to give the cumulative sensitivity values for regions away from the original features. Figures 34 and 35 show the extrapolated sensitivity maps in two dimensions, where as Figure 36 provides the same map in three dimensions.

The area sensitivity maps in Figures 34 to 36 are analogous to 'friction surface' maps in which different values of sensitivity can be thought of as friction components. As one travels across the friction surface, different levels of resistance are encountered that make it more or less difficult to move across different parts of the map. In this case, the closer one approaches areas of high sensitivity, the higher the level of friction encountered. A histogram of the 'friction levels' for Figure 34 is given in Figure 37.

The cumulative cost of travelling across the map in all directions was obtained relative to the starting point at Amauligak J-22. The goal is to determine the path from Amauligak to Richards Island that encounters the least 'environmental cost' along the way.

1. The area sensitivity map (Figure 34) was analyzed with *COST* in conjunction with a target image that provided a starting point at Amauligak to determine the cumulative cost to move in all possible directions away from Amauligak. The *COST* algorithm work in a pushbroom fashion and merely determines the total cost to arrive at each pixel location by adding the values of all pixels encountered along the way from the target image location to the pixel in question. *COST* then assigns the cumulative friction at that point to each pixel (Figure 38). In this regard, all points on the map were shown to lie somewhere uphill from the target location (Figure 39).
2. The *PATHWAY* module was then used to determine the least cost to travel from a location on the Richards Island to the target location at Amauligak (Figures 40). *PROFILE* was used to examine the relative cost to travel between these two points (Figure 41) and the final results displayed in three dimensions (Figure 42). Notice that the least environmental cost path to travel from Amauligak to shore in this hypothetical situation is clearly not the shortest route to shore. Bear in mind that the vertical dimension in these images are not topography but relative vulnerability.
3. By way of comparison, an alternative route was sketched by hand (Figure 43) and analyzed with *PROFILE* (Figure 44), which, when compared to Figure 41, clearly shows an increase in environmental cost to go directly from Amauligak to shore (Figure 45).

In a real situations, analyses such as the one above would require a considerable amount of fine tuning. Individual sensitivity values could be assigned to each section along the coast, more elaborate distance functions could be used for extrapolating sensitivity values into adjacent regions, and so on. However, the basic analytical approach of creating a friction surface, running a cost model, and finding paths of lowest cost would remain the same. The question arises as to how difficult it would be to incorporate modifications to the original friction surface to add, for example, new areas where access to shore would be prohibited or at least highly restricted.

Adding new areas for spatial analysis is relatively straight forward as outlined below. The nearshore area north of Richards Island surrounded by Garry Island, Pelly Island, Hooper Island and Kendall Island is designated as a Beluga Harvesting Area. Suppose that it was decided that this area was to be considered highly restricted to activities in support of hydrocarbon development; not entirely restricted, but just prohibitively expensive to access from an environmental cost point of view. How difficult would it be to add this feature to the raster image and assign it high level of access restriction followed by new route selections?

1. A polygon was created in QUIKMap in the vicinity of Pelly Island, converted to an IDRISI vector file format and rasterized and given a value of 1500, i.e., a sensitivity rating slightly higher than that of Tuktoyutak harbour area (Figure 45).
2. This new image was added to the original friction surface in Figure 34 using *OVERLAY* and choosing the 'cover' option to assign new sensitivity values to the Beluga harvesting area.
3. This image was made smaller by thinning the number of pixels in both X and Y directions by a factor of 4X using the function *CONTRACT* (Figure 46).
4. A digital elevation model was created for the new friction surface, plus a color mask for visualization purposes, using methods described earlier in this report.
5. Using the same source image for Amauligak, a new environmental cost image was created for the North Point area which now include special consideration for the Beluga harvesting area (Figure 47).
6. Finally, *PATHWAY* was used to determine the least environmental cost path from Amauliga to shore. Figures 48 and 49 show the new path entering toward the eastern side of Richards Island, clearing avoiding the Beluga harvest area.

Test 3
Planning for Environmental Conditions that Impact Borrow Deposit Surveying and Dredging Operations

Background

Many environmental and climatological factors affect the surveying recovery of granular deposits in the Beaufort Sea: weather conditions, visibility, ship traffic, and sea ice to name a few. Is it possible to visualize and analyses this type of information to improve planning of field operations? Do other data exist on a regional basis that might assist in planning borrow or environmental studies?

Two types of regional spatial data were examined Test 3. The first concerned regional bathymetry and the visualization of bottom topography and the production of depth profiles along possible pipeline corridors. The second category selected for Test 3 was sea ice distribution as a function of time, with particular emphasis on the occurrence of open water conditions which allow such things as marine seismic surveys, bottom sampling, shallow drilling or dredging to take place. The bathymetric data for this study was obtained from an inFOcus application prepared for the Royal Roads Military College and the data on sea ice conditions were obtained from the Beaufort Atlas describe in Test 2.

Beaufort Regional Bathymetry

The source map for rasterized bathymetry is given in Figure 50 in its original QUIKMap vector form and the borrow site locations are given in Figure 51. Notice how difficult it is to visualize the changes in elevation that occur across the area from the vector map alone. Figure 52 is the same map after rasterization and conversion to three dimensional perspective, looking toward the coast from the northeast. Figure 52 has a strong vertical exaggeration (about 60X) to visually enhance small topographic features. It was produced by a series of steps including the creation of QUIKMap polygons in vector format (Figure 53), rasterizatioin, the creation of a digital elevation model, and preparation of a special colour palette as in previous examples. A typical graphical output from this process is given in Figure 54 on which other features, like borrow site locations or pipeline routes, can be draped and visualized in three dimensions.

To extract information from such elevation data is relatively simple. To obtain a profile of water depths along a pipeline corridor, for example from Havik B-44 to Amauligak J-22 to North Point, the first step is to create a polyline in QUIKMap (red line in Figure 55). The equivalent diagram converted to raster format is given in Figure 56, although for this type of analysis only the transect of interest needs to be rasterized. A depth profile can be obtained directly by overlaying the IDRISI vector file on the digital elevation model for bathymetry (Figure 57). Notice in this case, the profile contains the artificial depths which can be converted to real depths using the equation Z2 = 2500-Z, where Z is the artificial depth that was used to avoid processing of negative numbers in IDRISI. To obtain a histogram of water depths encountered between Havik and North Point, it is necessary to first rasterize the transect profile into an image file. Next, the transect image file, whose pixel values are '1' only where the proposed pipeline route occurs and everywhere else '0', is multiplied times the water depths from the bathymetric DEM using *OVERLAY*. This, in effect, isolates the values of water depth that occur along the pipeline route, as all other pixels values in the new image are '0'. After conversion to real depths using the above formula, *HISTO* can be used to obtain a histogram of all water depths along the pipeline route (Figure 58).

In a similar manner, map algebra can be used to isolate other types of map features (sediment type, biological occurrences, etc.) and correlate this spatial information with water depth. For example, Figure 59 shows a histogram of the water depths for the ERKSAK borrow site. By multiplying the thickness of soft sediments map by the bathymetry map the location of soft sediments can be isolated (i.e., where the result of multiplication is (+) soft sediments occur and where '0' they are absent). Running *HISTO* on the new image provides a histogram which shows the relationship between water depths and the occurrence of soft sediments (Figure 60). In this case, soft sediments occur at a wide variety of water depths, so there is little difference between Figures 59 and 60. However, if there had been a strong correlation between these two variables, the difference would have been apparent. This approach could be used to carry tests such as tabulating the percentage of sediment types that occur along linear transects or within certain regions, the relationship between ice scours and water depths, and so on. Other statistical analyses are available in IDRISI, such as *REGRESS* for performing regression analyses.

Planning Survey Work For Different Environmental Conditions

The occurrence of sea ice can have a deleterious effect on survey and dredge operations. The Beaufort Atlas (Summary Map 10) provides a map of open water season in terms of median number of weeks between break-up and freeze-up.

The above map was redigitized from (essentially) line work to provide closed polygon coverage for open water seasons over the study region (Figure 61). Even in its original configuration with labelled contours, the vector map display is very difficult to interpret. Figure 62 shows this map converted to raster format along with a color code for different open water periods. The borrow sites are shown on this raster map in Figure 63.

The above information is displayed in three dimensions in Figure 64, which shows the relative position of borrow sites in white draped over a colour coded display where elevations correlate to number of weeks of open water. Only the northeastern portion of the ERKSAK borrow site appears to be generally accessible during a large portion of the summer period. Even within the ERKSAK site there appears to be variation, with the northeastern portion of the appears much more generally accessible than southern parts. Other borrow sites at ISSIGAK, ISSERK, and HERSCHEL Island seem less available during summer periods, with the southern portions of these sites being more favorable than the north.

Other factors may be considered simultaneously with variables such as the time periods of open water accessibility. For example, one could take into account time-based constraints such as special closures associated with environmental protection (for example during periods of Beluga calving or harvesting) or spatial constraints such as distance from shipping lanes.

In this test, the effect of open water conditions were combined with distance from land to produce a spatio-temporal type of constraints analysis. The rule of thumb was: the closer to land, the better.

Figure 65 shows the result of a distance analysis performed on the Beaufort coastline. Since the source maps are in latitude/longitude, the distance figures are expressed in term of degrees not metres. To produce Figure 65, a polygon of the Beaufort coast was exported to IDRISI, rasterized into an image file. This image was subjected to *DISTANCE* which provided a spatial analysis with values increasing away from land. However, in keeping with the above rule of thumb, these distance values were reclassified using *RECLASS* to make the values decrease with increase distance from land. The original data showed a range of 0 to 2.6 degrees which was divided into 0.2 degree intervals for the purpose of analysis. The order was reversed so that the highest values occurred along the coast.

Using *OVERLAY* the raster images for open water and the distance to land were multiplied together and the results are given in Figures 66 and 67 which correspond to two and three dimensional representations of the final results. The relative weighting functions in these types of analyses are important and require careful consideration if meaningful results are to be generated. In this case, values of 0 to 19 (corresponding to weeks of open water) were multiplied times values that range from 0 to 2.6 (distance in degrees from land). The variable 'open water' could be considered to be the dominant factor, especially where the effect of being close to land decreases with distance and the borrow sites are more or less the same distance from land. Using the *SCALAR* module, the relative values for DISTANCE were increased by a factor of 10 then multiplied times the open water image (Figure 68 and 69), which indicates that even with increased emphasis on the proximity to land the effect of open water accessibility still dominates.

The number of approaches that could be applied here are virtually limitless. Even such things as the cost of surveys could be analyzed on the basis of spatial and environmental considerations.

Pseudo Time Series Analysis of Open Water Conditions

As pointed out earlier in this report, IDRISI can be used for time series analysis. The images of total open water used above can be also be used in a crude way to visualize the manner in which Beaufort Sea opens up in during summer periods. By assuming that the areas with the largest amount of recorded open water periods (in this case 19 weeks) also were the first areas to open up, and conversely, the areas with minimal open water periods are the last to open up, IDRISI can be used to overlay a series of related maps in rapid succession to create a quasii-animation. The visual impact of this technique can be quite dramatic.

Although a raster time series for ice opening in the Beaufort will not be presented here, the reader can get a feel for how such a sequence might appear by viewing the last few figures for this report while minimizing the time delay between each slide. Figures 70 to 88 provide a rough approximation of how the Beaufort Sea is transformed from completed covered to nearly open water conditions over a period of about 19weeks.

CONCLUSION

The IDRISI raster GIS satisfies many importance analytical requirements for constraints analysis in association with marine granular resource development in the Beaufort Sea. All of the standard GIS functions such as distance functions, overlay and classify, digital terrain modelling are well represented in the software. There is even some capability for time series analysis over time and space. The quality of output images also seems suitable and at $150 for a 10 user site license makes this system the least expense GIS that is commercially available for its performance level. Also, IDRISI has powerful functionality in the areas of satellite image processing and statistical analysis, neither of which were tested in this investigation. The conversion from QUIKMap basemap and database format to IDRISI was reasonably efficient except where old, unstructured basemaps were used.

IDRISI is somewhat difficult to penetrate, especially since it was written for a classroom type of environment where students have direct access to technical help. For example, two software manuals come with the system, one is a technical reference guide with detailed descriptions of individual commands and the other is brief tutorial on raster GIS and how to use IDRISI. Neither manual has an index. Thus, it is difficult to learn how to use the system other than by trial and error. Also, IDRISI is a raster-based image processing and some of the advantages of quad-tree GIS database architectures (higher resolution in detailed areas, reduced disk space) make these systems attractive for production GIS activities. However, in terms of price and performance, for general environmental constraints analyses the IDRISI system provides sufficiently strong capabilities that most non-technical users would be satisfied with its analytical capabilities.

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