FISH HABITAT MAPPING USING ACOUSTIC AND GIS TECHNOLOGIES

By

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A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
For the Degree of

MASTER OF SCIENCE

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

A rapid and accurate the method of assessment for fish habitats is a growing need as there is increasing degradation of aquatic environments world wide. While several small Canadian companies have developed useful technology to assess fish habitats, their ability to manage and integrate data into geographic information system (GIS) is limited. The first objective of this thesis was to evaluate the methods for undertaking and assessing the acoustic classification of substrates for five freshwater systems ranging from a prairie river (Red River), to a Canadian Shield river (Winnipeg River), to a northern Canadian river (Mackenzie River), to small northern and Arctic lakes (Chitty Lake and Wormy Lake using a QTC VIEW^{TM} and a QTC IMPACT^{TM} (a package of hardware and software made by Quester Tangent Corporation). The Red River has few major substrate classes while the Winnipeg River has more numerous, rapidly changing, small-scale substrate patterns. The Mackenzie River, on the other hand, is a large river with large-scale homogeneous substrates allowing for the collection of many acoustic signals from one substrate type and making the correlation of acoustic signal and substrate classes easier. Ground truth was undertaken by collecting benthic samples and developing a "visual classification system" and a process for the separation of sediments based on grain-sizes and proportions. A geographical information system (GIS) was developed in which the acoustic data were used to interpolate into continuous bathymetry and substrate patterns. The second objective was to determine if a comprehensive catalogue of substrate classes could be developed, to correlate them with the benthic samples, and to relate the bathymetry models and the substrate classes to fish movements, i.e. lake sturgeon, *Acipenser fulvescenes*, lake trout *Salvelinus namaycush* and Arctic char *Salvelinus alpinus,* in a spatial context. To expand the understanding of substrate, the track points of lake sturgeon movements were superimposed on interpolated maps of the bathymetry and the substrate patterns at the Seven Sisters site on the Winnipeg River. The movements of lake sturgeon, lake trout and Arctic char were tracked in the three systems using a VEMCO's acoustic telemetry system. Additional selected samples of lake trout and Arctic char movement records (two fish of each species from each site) were assessed to verify the association of the fish movement and the substrate maps

developed from the acoustic data from Chitty Lake and Wormy Lake. The frequency of occurrence over certain substrate types will help biologists define fish habitats.

It is recommended that 1) the acquisition of high resolution data from the QTC VIEW be accomplished by reducing the boat speed and decreasing the distance between transects to determine if the acoustic signal is more variable from complex substrates and 2) for studies on fish movements reduce battery power of acoustic tags to limit the detection range by VR2 receivers and thereby improve resolution.

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CHAPTER 1 INTRODUCTION

Challenges in describing fish habitat

The increasing anthropogenic pressures on freshwater resources in Canada have resulted in the development of legislation dealing with fish habitat that incorporates the doctrine of "no-net-loss". This means that any unnatural perturbation of fish habitat requires compensation either through improvements in the perturbed area or by adding habitat in another area. A major problem concerning the enforcement of regulation (Fisheries Act) is a lack of good fish habitat data on which to base mitigation, particularly in cases dealing with irrigation and hydroelectric impoundments, mining, and oil and gas developments. Since the impact of such operations can be significant, there is a need to develop methods that rely less on descriptive indicators and more on reproducible and quantitative data.

One approach assumes that habitat quality is directly reflected in the patterns of utilization by fish, such that the highest quality habitat supports the highest concentrations of fish (MacCall, 1990; McConnaughey, 1995). This approach often uses habitat descriptors related to habitat quality including water depth, substrate types, rugosity, slope/aspect, water currents, sediments and water chemistry. Researchers have tried to evaluate the different quality of habitats in terms of available physical and ecological variables, each of which was used to describe a particular aspect of habitat characteristics. Most of the habitat descriptions are either too general or too detailed and seldom provide comparable or reproducible results across studies.

Even though some variables can be measured quantitatively at survey sites, the integration of the different kinds of data becomes problematic without the geo-positions. Published data usually does not contain the complete spatial extent of the habitats utilized geographically by the fishes, but the habitat models have been built (Beamish and

Lowardz, 1996, Clark, et al., 1999, Riou, et al., 2001). The relationships between the sediment composition and the benthic community structure also have been analyzed (Dickson and Lee, 1972; Shelton and Rolfe, 1972; Kaplan, et al., 1977; Bonsdorff, 1983; Van der Veer, et al., 1985; Hall, 1994, Seiderer and Newell, 1999). Surficial sediments are clearly important to demersal fishes (Scott, 1982; Perry et al., 1994) and substrate type has been correlated with depth (Sharma, et al., 1972, Ojeda, et al. 2004).

Deterministic mathematic models have been using multivariate analysis to incorporate variables that influenced the distribution and abundance of aquatic animals, e.g., the correlation of benthic fauna with bathymetry along the lower Mackenzie River (Copeland, 1982). Use of a mathematic habitat model can at best simplify ecological processes and may be useful to correlate alteration of habitats (Copeland, 1982). These models have not resolved large scale data transacts with precise tracking and geo-referencing of fish habitats. It is uncertain if these models can effectively map habitats since many variables or parameters are calibrated non-synchronically (Stoner, et al., 2001), nor can they correlate water depth and substrate type in multiple associations.

Rather than attempting to account for as many variables as possible, it was suggested that only the key variables be evaluated with respect to fish habitats (Schroeder and Vangilder, 1997). For example, water depth with massive geo-referencing points has often been tailored to create a single purpose model that represents habitat. It is well known that depth or bathymetry data is usually recorded as x, y, z point data, and can be used to generate depth contours (line and area vector data) as well as bathymetric raster models. The bathymetric contribution to the benthic habitat characteristics demonstrates the topographic variation of sea/river/lake floors and from this data, bottom morphological features such as slope and aspect can be derived.

Substrate is material that makes up the bed of a body of water. It provides a cover and a spawning habitat for many fishes and food such as benthic invertebrates (Simonson, et. al., 1994). Unlike water depth, however, a substrate itself is not a spatial scaling concept but a physical entity. Substrate must be identified directly (i.e. underwater photography, ground truth) and/or requires discrimination among classes of substrate (i.e. use acoustically remote sensing for collecting large data sets where each sampling position is pinged as x, y, z spatial data).

Acoustic data was used to identify the depth and the substrate to estimate the spatial extent and suitability of sole (*Solea solea*) nursery grounds in the Dover Strait (Eastwood, et al., 2003). Geo-referencing and digitization of bathymetric and substrate data based on the geographic information system (GIS) have been used to map the benthic habitats (Urbanski and Szymelfenig, 2003) and to design the essential fish habitat (Cheney, et al., 2003, Valavanis, et al., 2004).

The U.S. government requires, for aquatic conservation purposes, that the two data sets involving geo-visualizing depth and substrate type be used to describe fish habitats (Document, 1997, Simonson, et al., 1994). Canada has similar requirements for environmental and ecological assessment for marine protected areas (Fisheries and Oceans Canada, 1997).

A variety of remote and direct methods are available for acquiring depth and substrate data including: acoustic, electro-optical, physical and observational. Remote assessments (satellite images and aerial photographs, shipboard acoustic surveys) tend to characterize relatively large areas (on the order of hundreds to many thousands of square meters) and yield characteristic information and massive data. Data from acoustic assessments are widely employed to produce habitats which are described in terms of depth and sediment characteristics (e.g., Hamilton et al. 1999). Direct methods (lead lines, underwater photograph, sediment sampling) allow researchers to take a closer, fine-scale look at smaller sections of a water system.

The choice of the method to be used should be based on the geographic extent of the project (scale), the resolution (data density), and sampling availability (data type) and in turn, are based on the purpose and the goals of the project.

Objectives

The objectives of my thesis were: 1) to create a bathymetry model from acoustic data and to assess this acoustic technology in order to describe the substrate in a variety of freshwater aquatic systems ranging from prairie rivers, to northern Canadian rivers, to small northern and Arctic lakes. 2) to evaluate the application of the acoustic technology (QTC VIEW Series 5 has not been not widely applied to a variety of freshwater systems to date) and to begin to build a catalogue of substrate classes that correlate with the actual field benthic samples, and 3) to relate the bathymetry models and the substrate classes to the fish movement and the frequency of occurrence is shown on bathymetry and substrate types in a spatial context. The three fish species evaluated are lake sturgeon *Acipenser fulvescenes*, lake trout *Salvelinus namaycush* and Arctic char *Salvelinus alpinus* in different types of aquatic systems.

CHAPTER 2 LITERATURE REVIEW

The primary focus in this section is to review the applicable approaches for measuring water depth and aquatic-floor substrate, interpolation techniques suitable for modeling bathymetry and characterizing substrates, as well as telemetry methods for charting fish movement and habitat use.

Value of manual techniques

Bathymetry tools

There is no historical record of when and what bathymetric tools were "invented" by man. One can only imagine how simple the ancient tools might have been, such as straight wood sticks, tree boughs, branches and poles for shallower waters; long lines or ropes with stones or other weights for deeper waters. Yet a few simple but practical tools such as marked poles and lead lines are still used today for field surveys because of their easy portability and low cost. It is still necessary to use such tools for the observation of the constant changes of water levels (hydrological and navigation signal) or for taking a measurement of *in situ* depths (for diving, calibrating or sampling).

These old bathymetric tools have not been able to keep up with new technologies. The measurements are inaccurate when taken from a small number of sampling sites and it is difficult to reach the bottom of deep water.

Substrate samplers

The assessment of substrate types has traditionally relied on manual sampling programs for sediment classification, but collection of the samples of sediments from the bottom of rivers, lakes or oceans is difficult. The early geological bottom samplers were comprised of five groups: scraper or drag buckets, chambered weights, the snapper or grab-bucket samplers, coring tubes and rod samplers (Twenhofel and Tyler, 1941). Two kinds of samplers (grab and corer) were used in benthic habitat surveys. Grab sampling is a common technique available for the examination of the surface sediment (from about 10-15 cm deep) (Holme and McIntyre, 1984). The sediment corers provide a vertical cross-section of the sediment column and the type of corer used depends on the substrate materials, the interval of interest, and the volume of materials required (Holme and McIntyre, 1984).

Physical characteristics

Tools should be simple, portable, durable, economical and easy to use. At the present, marked rulers are widely used to measure and monitor water level or to signal for submerged rocks. Samples of sediments can be described based on sediment composition and texture. If necessary, the history of an area can be determined through the analyses of sedimentation rates, magnetic properties, total organic carbon, grain size sampling, trace metal concentrations, and organic pollutants. Furthermore, data acquired from the remote techniques for determining the bathymetry and the substrates also need to be calibrated and interpreted based on the physical results from manual work.

Limitations

Bathymetric tools and grab samplers are relatively light and easy to operate. However, the approach is labor-intensive and time-consuming and because fewer survey points are available for larger water areas, great biases are likely to occur during interpolation. Interpreting these observations in a spatial context has proved difficult due to the lack of information on the topographic structure and sedimentary texture of the adjacent sea/river/lakebed. Under some conditions, manual bathymetric tools do not work at all. For example, it is impossible to measure a deep ocean using these tools. Additionally, grabbing disrupts the structural integrity of sediment distributions (Guigne et. al., 1993), and grab samplers are designed for soft sediments, so a hard bottom cannot be sampled effectively.

Development of acoustic techniques

Sounding of water depths

New measuring tools were designed as early as 1826 to explore the deep ocean (Kunzig, 1999) and consisted of a church bell, a hammer, a flare, an ear trumpet and a tin pipe. The speed of the underwater sound was calculated from the delay between observing the flare and hearing the bell. The theoretical significance was obvious, although the result was incorrect when compared to current techniques. At that time, it was easy to echo-sound the depth in principle, but in practice it was difficult to measure the intervals accurately. There was no breakthrough to reduce the error in echo-soundings until the nineteenth century (Deacon, 1971).

The Fathometer, a registered trademark often loosely applied to all depth-sounding gear, was developed in 1914 for iceberg detection and based on research by Canadian engineer R. A. Fessenden (Drubbe and Rust, 1954). Fessenden's oscillator became the sound source of the first practical deep ocean echo sounder by transmitting the pulses of sound at an interval that could be varied by the operator. Two earphones were connected to the transmitter and to the echo receiver respectively to find out the number of sound pulses traveling in the water. The application of echo-sounding principles for submarine detection during World War II resulted in the development of a 'fathometer' to sound all ocean depths. At that time, the "fathometer" was mounted on a ship to make continuous bottom profiles, but it was plagued by power supply failures. Further constraints showed that measurements were not sharp, i.e., the sonar ping spread out over an area of seafloor several miles across, and therefore the echo and the resulting depth measurement came from some point in that area, but the specific point was unclear. Following World War II, electronic echo-sounding was the common system in use for delineating the bottom. In 1954 an advanced, highly accurate echo sounder called the Precision Depth Recorder (PDR) was developed. This machine measured depths with errors of less than one percent for the total water depths. The PDR discovered abyssal plains, the flattest places on Earth. This was, perhaps, the single most significant bathymetric discovery made since the beginning of deep ocean exploration. As such instruments collect discrete point data along survey track lines; they are referred to as single-beam acoustic depth sounders.

By the early 1960s, the U.S. Navy had designed a new multi-beam sounding system called the Sonar Array Survey System (SASS). This system collected bathymetric soundings across a swath of the seafloor using an array of acoustic beams, acquired dense sounding data along and between track lines and provided accurate, high-resolution, 100 percent coverage of the seafloor over relatively large areas. Such sounding arrays, coupled with accurate navigation, allowed the immediate generation of accurate sea-floor maps.

Single-beam vs. multi-beam bathymetry

Over the last two decades, most bathymetric data were collected as discrete points along survey vessel track lines using single-beam acoustic depth sounders. Single-beam depth sounders have several advantages, as they are commonly available at a relatively low cost, and portable units can be easily deployed on small boats or ships. In addition, they can be interfaced with acoustic substrate classifiers that estimate seabed composition (described as Acoustic Substrate Classifiers).

Multi-beam bathymetry systems have dramatically improved our ability to acquire continuous high-resolution depth data. Bathymetric data with horizontal postings of less than one meter are now routinely collected over wide areas using multi-beam techniques. Multi-beam sounding systems provide greater bottom coverage than a single-beam system (their coverage is based on the length of the transducer boom). These systems are typically mounted semi-permanently on designated boats. They are far less portable than single-beam systems and may restrict boat maneuverability.

The choice between the single and multi-beam systems is a compromise in the requirements of the survey, working conditions, and the availability of suitable instruments. If the survey covers large and complex areas of the sea/river/lakebed and requires complete bottom coverage, then multi-beam systems may be the better option. If lower resolution is acceptable, then single-beam bathymetry in conjunction with other techniques (such as side-scan sonar) may provide a lower cost alternative.

Acoustic substrate classifiers at birth

As previously mentioned, physical substrate samplers, whether grab samplers or corers, are useful for classifying sediments. However, the application of these high-confidence methods of substrate classification in large area mapping projects is costly in terms of money and effort. While the resolution of sediments classes from the core and the grab samples can be high, the samples must be very closely spaced in order to give a good spatial (x, y) resolution.

Concurrent with the development of single-beam and multi-beam depth echo sounders, different substrates detected by their acoustic reflectance or backscatter properties were developed. Imaging of the seabed was revolutionized in the 1940's when the first side scan sonar system was produced (Kenny, 2000). Seabed classifications had a wide application in the early 1970's, and were inferred from the echo intensity and the echo comparison through the visual examination of analogue records (Simpkin and Collins, 1997). Most of the recent developments (during 1990's) in acoustic mapping have been associated with the increase in digital processing offered by modern computer technology.

Two new single-beam systems (RoxAnn^{TM} and QTC VIEW^{TM} system) are based on digital signal processing techniques that allow for the measurement of water depths and the discrimination of different seafloor characteristics at the same time (Collins et al., 1997; Chivers et al., 1990). The pivotal advantage of the systems is their capability of discriminating substrate features (Orlowski, 1984, Burns, et al., 1985, Jackson and Briggs, 1992, Keeton and Burle, 1996). RoxAnn (Marine Micro Systems Ltd, Aberdeen) facilitated the first and second echo returns in order to perform bottom sediment classification (Burns et al., 1985). This method was first used by experienced fishers using regular echo sounders (Chivers et al., 1990). QTC VIEW^{TM} (Quester Tangent Corporation, Sydney, Canada) is operated in a very different way than RoxAnn. That is, the first returning echo is selected for waveform analysis. The time when the QTC VIEW^{TM} system was put into use is roughly inferred from Collins' paper (1996). The processing raw data algorithm of the two systems demonstrated some similarities in removing erroneous or unreliable points and in using k-means cluster (Wright, 2002; Smith, et al., 2001)

Equipped with side-looking transducers that send out sonar signals in pulses across the seabed, side-scan sonar is a relatively new seafloor mapping technology. Side-scan sonar systems are very accurate for imaging large areas of the seafloor. They are capable of producing continuous characterization information of the seafloor at all depths. Lower frequency systems (around 100 kHz) provide wide swath coverage and are used to create mosaics of the entire survey area. Higher frequency systems (300 kHz and above) can provide higher resolution images. These data reveal detailed information of distinct objects or of features on the seafloor. These higher frequencies have shorter ranges and are generally used to image a particular feature or area of interest. Some side-scan sonar systems are very sensitive and can measure features smaller than 10 centimeters (less than 4 inches) on the ocean bottom. However, there is a trade-off between the time required to map an area and the resolution or detect ability of the seabed features within the mapped area.

RoxAnn™ vs. QTC VIEW™

Compared to the two processing algorithms, the waveform analysis in the QTC VIEW™ seems more complete and logical than in RoxAnn. In terms of their performances, the QTC VIEW™ system generally has consistent sediment grain size properties and gives a better classification than dose RoxAnn system (Hamilton, et al., 1999).

RoxAnn has been used to study lake sturgeon habitat (Dick, 2004), but has numerous limitations. The equipment could not operate below 12 – 14 °C. Boat speed was relatively slow. The design was cumbersome and the equipment was heavy to use in the field. Another limitation was that the RoxAnn only measured the hardness and the softness, the two echoes and sometimes produced confounding results because the signal could be additive and misrepresent both the depth and the bottom type.

Theory and practice of QTC VIEW™

Basic Principle

The QTC VIEW™ system is based on the principle that an echo sounder generates a short pulse of sound at a single frequency (Urick, 1983). The time interval is measured for the water depth when the pulse moves down through the water and bounces off the seafloor (Mitson, 1983). Physical substrate characteristics can be simultaneously decoded from the bouncing pulse (echo waveform): the extent to which sound is absorbed or reflected by the floor depends on the hardness of the bed while the time

/strength of the decaying echo may contain the element that refers to roughness (Burns, et al., 1985). Consequently, the attribute of an echo from the system includes both the depth and the substrate characteristics.

The returning echo is converted from analogue form to digital form and then is subjected to analysis using a large number of algorithms for waveform analysis (Collins, et al., 1996, Collins and McConnaghey, 1998). The echo was influenced by seabed echo properties such as the seabed hardness and the sediment grain size (Smith et al., 2001). Some researchers have done considerable work on QTC data to improve substrate classification where data is processed through a principal component analysis (PCA) and K means for acoustic classes (Legendre et al., 2002).

Application scope

QTC VIEW™ systems are now established as a standard for scientific data acquisition in nearly twenty countries. The main body of users includes fisheries habitat mapmakers, marine geoscientists and hydrographers (Collins, 1999). The potentially important application of this technology is to map fish habitat depth and substrate or the distribution of benthic animals. In addition, acoustic seabed classification has been used to monitor dredging in a coastal environment (Wienberg and Bartholomä, 2005). Acoustic discrimination techniques have just recently been applied to map riverbeds (e.g. Maushake and Collins, 2001), although marine surveyors have used echo sounding to classify seabed for many years. The QTC VIEW™ Series V (QTC5) system represents a new generation of single beam seabed classification from Quester Tangent Company. The QTC5 system achieves accurate, repeatable classification in less than 1 meter in depth, overcoming the challenges of greatly varied water environments. That makes it possible for the application of the QTC VIEW™ system to rivers or lakes, yet there are fewer publications from these areas. Since 2001, Dick (Dick, 2004) has applied the QTC5 and its earlier version to a variety of freshwater aquatic systems ranging from two prairie rivers to northern Canadian rivers to small northern and Arctic lakes. The preliminary assessment of this acoustic technique predicts wider use in freshwater systems.

Most researchers are focusing on exploring substrate patterns in terms of the real time acoustic data from QTC VIEW™. This data is processed using a regular procedure recommended by the QTC IMPACT™ manual (2002) for an initial unsupervised classification. Little difference has been demonstrated on the choice of the two split decision indicators (the total score and the Cluster Performance Index (CPI) rate). Neither appears to have an objective reference to indicate optimal levels. At the end of the procedure, echoes with similar characteristics form clusters that define acoustic classes and these classes have a statistical variance. This means that catalogue data cannot give any detailed physical information regarding sediment types without verification by benthic samples.

Field-acoustic calibrations differ among studies. Anderson, et al. (2002) used four different habitats (mud, gravel, rock, and macro algae on rock) for the calibration of the QTC VIEW™ system. Ellingsen, et al., (2002) demonstrated that the acoustic classifications were generally in accordance with the sediment grain sizes and were most likely to be influenced by the softness of the substrate in Fraenfjorden, western Norway. Similar sediment classification was performed for the verification of acoustic classes in Ria de Aveiro, Western coast of Portugal (Freitas, 2003).

All of these approaches shared a common goal, i.e. to address the problems of ground truth accuracy and reliability. Most had their own benthic data/samples acquisition designs, but separate into two groups: direct verification (benthic samples, video photographs and submersible observations) and indirect confirmation (multivariate analysis).

Initially, benthic samples were acquired with grabs or corers when acoustic surveys were done and were positioned to cover as great a range of the acoustic survey as possible and the sample sites were located on the track lines. The different dominant (e.g. Ellinsen, et al. 2002) or grain-size ordination (Freitas, 2003) fractions of sediments were directly related to the acoustic classes. In order to improve the reliability of the benthic sample verification, video photographs (Hutin, et al. 2005) or divers' observations (Anderson, et al. 2002) complemented the sediment classification if benthic samples were not available. Occasionally, side-scan sonar was coupled with the QTC VIEW™ and video to differentiate the patterns between homogeneity and heterogeneity if necessary (Hewitte, 2004). The best scenario is to combine all of the above devices for the direct verification, but at the same time the efforts and cost need to be considered.

Statistical estimates are cheaper and quicker if strong correlations exist between the sediment geotechnical attributes and the acoustic signals. Preston et al. (1999) discovered that the bearing strength was the major contributor to the first geotechnical canonical variable of four geotechnical variables (the three others were seabed grain size, shear strength and porosity). Another problem occurred when the bathymetry was correlated with the substrate distribution. The areas of similar depths were associated with the range of fuzzy clustering values, and were classified as a bottom type without assigning specific physical characteristics to the class (Hoffman et al. 2002).

Advantages and limitations

The advantage to using the above single-beam acoustic substrate classification systems is its low cost, its portability and minimal power requirements. It is also capable of collecting massive data quickly, a requirement in the creation of a bathymetry model and substrate patterns.

These systems are highly dependent on field calibration, so the data they produce are very difficult to interpret without physical sampling, visual verification, or image collection. Additionally, their narrow swath width makes continuous coverage of the floor of waters difficult, and their acoustic "footprint" is relatively small and dependent on depth.

Three obvious limitations of these systems are: 1) Incapable of spatial analysis such as draping or overlaying, even the simplest site points can not be overlaid on the acoustic track points for ground truth. 2) Data is a specific format that cannot be transferred conveniently. 3) Inability of the user to modify the specific interpolation algorithm (QTC CLAMS^{TM}) on the acoustic data provided by the company.

Interpolation

From the previous discussion, it is clear that the available bathymetry data and the substrate data come from the acoustic tracks and the grab samples that are localized at the point sites. Although it is possible to show and the interpret results and the attributes of these discrete points in space, there are two problems to overcome: the extent of the untracked area of interest and incomplete spatial display (Borrough and McDonnell, 1998). It is far easier to address the above problems if the original point data are converted into continuous images, but interpolation is required to predict the value of the attributes at the non-sampled sites from the known measurement of point locations within the same area. Caution is advised in the interpolation as its successful application depends on the size and the density of the data set and the careful selection of interpolation methods.

Interpolation methods

Several interpolation methods are available for converting the scattered point data into a continuous surface. Goodchild (2002) and Sharma (1999) classify these methods as follows: point interpolation and areal interpolation, global and local interpolators, exact and approximate interpolators, stochastic and deterministic interpolators, gradual and abrupt interpolators. According to the nature of the field sampling, most data are points that are operated and passed through using the concept of randomness within a small zone. Finally a continuous smooth surface is produced with gradual changes occurring between the observed data points. Generally, a gradual-local-exact-stochastic-point interpolation is achieved with the modern GIS applications. The major interpolation methods for the points are Triangulated Irregular Network (TIN), Inverse Distance Weighting (IDW), Kriging, and Topogrid methods.

Triangulated Irregular Network (TIN)

The TIN is one of the most simple and exact methods of the interpolation techniques. It is useful for irregularly spaced points. With this method, the known data points are connected by lines to form a series of triangles. Since the value at each node of the triangle is known and the distance between the nodes can be calculated, a simple linear equation can then be used to calculate an interpolated value for any position within the boundary of the TIN. The TIN model is also used to generate digital terrain models.

Kriging

Kriging, also known as the "Theory of regionalized variables", was developed by G. Matherson and D.G. Krige as an optimal method of interpolation for use in the mining industry (Trodd, 1999). The Kriging method is based on the recognition that the spatial variation of any continuous attribute is often too irregular to be modeled by a simple, smooth mathematical function. Instead, the variation can be better described by a stochastic surface.

Inverse Distance Weighting (IDW)

The inverse distance weighting interpolation method assumes that the unknown value of a point is influenced more by nearby control points than by those points farther away. The degree of weight is expressed by the inverse of the distance between the points raised to a power. The weight of a sample point is assigned according to the inverse of its distance to the point being estimated.

Topogrid (command in ARC)

The TOPOGRID is an interpolation method specifically designed for the creation of hydrological correct digital elevation models (DEMs) from comparatively small, but well selected elevation and stream coverages. It is based upon the ANUDEM program developed by Michael Hutchinson (1989). ANUDEM produces grid-based DEMs and calculates values on a regular grid of a discrete smooth surface fitted to large numbers of irregularly spaced elevation data points.

Aquatic interpolations

Many GIS interpolation techniques (including TIN, Kriging, Topogrid and IDW) have been very successful in terrestrial studies. However, GIS is a new application to aquatic systems. Most fish habitat researchers have been content with using raw data storage and display (e.g. Stanbury et al., 1999) as very few spatial analyses have been attempted. There needs to be a link between an ecological model with GIS for pre-processing (e.g. coordinate transformation, projection conversion) and for post processing (e.g. cartographic and visual display, simple spatial analysis) of the data. Maury and Gascuel (1999) presented an aquatic environment simulation model interfaced with a GIS that was employed as a post processing tool for display and analysis of model results.

Digital Bathymetry Model (DBM)

Specific steps are required when these methods are applied directly to an underwater field. A digital bathymetric map for an essential fish habitat designation (Valavanis, et al., 2003) was made through processing (Kriging) of a point datasets derived by combining the available depth soundings with high resolution of marine gravity information from the Geosat and the ERS-1 (Smith and Sandwell, 1997). The spatial resolution was 50 m from the 10 km of raw data. Carter and Shankar (1997) performed a bathymetry interpolation study with ordinary kriging and concluded that the interpolation of the regular grids from an irregularly collected field data is a complex procedure that requires more than just an automatic application of a geo-statistical technique.

Burroughes et al. (2001) used an inverse distance weighting (IDW) scheme to interpolate the bathymetry data from the Truro River in southwest Cornwall, UK with the following modifications: manual editing of the sounding data to locate the line of maximum depth along the channel; and defining three different zones namely, the central, the east, and the west. These modifications led to the division of the river into three zones along the river and when the IDW was applied to the modified data, the resulting surface was significantly better as compared to the surface generated prior to the modifications. These modifications enabled the interpolation scheme to be applied to the longitudinal stretches thus creating a more accurate riverbed.

Digital Substrate Model (DSM)

All remotely sensed data (aerial photograph, satellite imagery) are in relation to the physical landscape in a terrestrial ecosystem, and guidelines on sample size, ground truth and techniques for assigning grid cells to vegetation classes and habitat utilization were developed and tested. However, transferring this application to underwater terrain is consequently not possible due to the lack of visibility of the underwater features displaying by the optical electronic systems. Consequently, only inter-tidal and shallow sub-tidal areas with clear waters have been able to directly benefits from the use of this approach. Remote acoustic assessments were used for mapping sediments due to the strong link between sediment characteristics of the seafloor and the returning acoustic signal. In this way, the continuous coverage of side-scan sonar was increasingly used for sediment classification with verification of benthic sampling or videoing (e.g. McREA Jr. et al, 1999, Hewitt, J. E. et al. 2004). This method provides an important source for the digital substrate model (DSM).

Assessment of interpolation methods

The quality of interpolation can vary greatly depending on the data source and the interpolation techniques. Even with a high quality data source, two types of errors (numerical and geometric) are likely to occur when predicting values are interpolated from measured points. The differences in the results are produced by different algorithms for estimating geo-morphological characteristics such as gradient or aspect. A simplified analysis, Root Mean-Square Error (RMSE), is often used for assessing numerical accuracy. By contrast, the algorithms of the geo-morphological fitness were more focused. For example, the evaluation of digital elevation model (DEM) in terms of their representation of the surface aspects was examined by Wise (1997 and 2000).

TOPOGRID uses knowledge about surfaces and imposes constraints on the interpolation process that results in a connected drainage structure and corrects the representation of the ridges and the streams (Hutchinson and Dowling, 1991). Specifically speaking, ANUDEM has many features that are not found in other interpolation programs such as: 1) the process is computationally efficient, hence, DEMs with over a million points can be easily interpolated using a computer workstation; the roughness penalty (one of the interpolation parameters) can be modified to allow the fitted DEM to follow the sharp changes in terrain associated with ridges and sometimes with streams and other land features; and 2) the program uses a drainage enforcement algorithm that attempts to remove all the sinks in the fitted DEM which have not been identified by the user. In contrast, TIN, Kriging and IDW were originally designed to interpolate terrestrial data from all even directions, so they are probably not suitable for drainage patterns with many ridges and streams influenced by an unstable water flow.

Telemetry

Telemetry using acoustic and radio tagging is a widely applied technique in fisheries studies. However, since combining fish movement data with geo-referenced map of bathymetry and substrate is more recent application, this section reviews current technologies used in fish movement studies. There are two methods (mark-recapture and telemetry) in monitoring fish movement. In a small stream, the pattern of movements of small adult fish or juveniles of large species is still studied by tagging and recapturing the fish because of the high recapture rate i.e. 52.3 – 64.9% (Bridcut and Giller, 1993; Aparcio, et al. 1999). To date, two telemetric systems (ultrasonic and radio) are used to describe fish movement studies.

Ultrasonic telemetry was first explored on the adult chinook salmon (Trefthen, et al., 1957), and pilot radio telemetry was used for measuring deep body temperature of dolphin (MacKay, 1964).). It is worthwhile to note that the ultrasonic methodology is virtually limited to conditions of study where high conductivity or great depths interfere with sonar signal transmission / reception. In contrast, radio signals can be located entirely in the air or through the ice and are unaffected by turbulence, algae or macrophytes in the water. Both techniques have played a critical role in advancing knowledge of fish movements and habitat use.

Selection of telemetry system

Choice of a telemetry system needs to consider size, weight, shape, life, physical and electrical stability and power (Cochran and Lord, 1963). In general, ultrasonic telemetry tends to be used in saltwater, fresh water with high conductivity and deep water while radio telemetry is suited to track large areas to identify mobile species in shallow, low conductivity and turbulent water.

Transmitter attachment methods

After nearly 50 years of experimentation, three techniques of transmitter attachments, stomach insertion and surgical implantation have been developed. The method of choice depends on the morphology and behavior of species, habitat, size, method specific, or the interaction of factors. Their effects on fish behavior are obviously different.

1. *External attachment*

An external transmitter is easier to attach and causes little insult to fish. It is useful if the fish are to be released immediately or when the data is collected over a short period. This method affects fish swimming performances because of increased loads, drags, or local inflammations. Compared to that of controls, McCleave and Stred's study (1975) demonstrated that externally placed dummy radio transmitters on Atlantic salmon smolts caused a highly significant decrease in swimming speed. Some small species like yellow perch with externally tagged dummy transmitters were more susceptible to predation and more sensitive to environmental stress than those of the control group (Ross and McCormint, 1981). Changes in pelagic fish swimming behavior, i.e. cowrose ray, occurred before and after the attachment of an external, buoyant transmitter (Blaylock, 1990).

2. *Stomach insertion*

A transmitter is inserted with a special probe, used to push the transmitter through the esophagus and into the stomach. Following the insertion, the probe is withdrawn leaving the transmitter in the stomach and the leads or antenna emerging from the esophagus. Mellas and Haynes (1985) concluded that stomach insertion was the best method of transmitter attachment by testing rainbow trout *Onchorhynclus mykiss* (formerly *Salmo gairdneri*) and white perch (*Morone americana*) in physical, behavioral and ecological constraints. According to the frequency of recapture of spawning white bass, the highest recovery percentage (18.8%) of those with stomach insertion was found in the three attaching ways. In spite of these results, failure to reach spawning sites was recorded with inserted transmitters (Gray and Haynes, 1979).

3. *Surgical implantation*

The methods described previously have the common disadvantage of not being able to undertake long term studies because of high loss or regurgitation of transmitters. Biologists generally prefer surgical procedures for implanting transmitters into the peritoneal cavity as results indicate that this is better for a long duration studies (Hart and Summerfelt, 1975; Stasko and Pincock, 1977; Lucas, 1989). Surgical implantation has two long term negative effects on the fish if the weight of transmitter is improperly factored to fish weight. No mortality and lag of growth was noted over 112 days after surgery of adult channel catfish *Ictahrus punctatus* (Summerfelt and Mosier, 1984). A similar report was shown for rainbow trout *Onchorhynclus mykiss* (formerly *Salmo gairdneri*) with surgically implanted transmitters (Lucas, 1989). With improvements in electronics, battery life, and less weight, this technique was also applied to juvenile and small species of fish. Result from studies with Atlantic salmon (*Salmo salar* L.) smolts and parrs indicated no significant effect on growth, feeding, swimming behavior or stamina. Little effect on bluegill movements was reported for implanted ultrasonic transmitters over six months (Prince and Maughan, 1978).

The main disadvantage of surgical implantation is the length of time for surgery, recovery period and infection. Loss of implanted transmitters has occurred due to loss of sutures (Summerfelt and Mosier, 1984; Marty and Summerfelt, 1986).

Receiver deployment

Contrary to numerous transmitter attachment studies, only a few reports regarding receiver deployment have been documented (Niemela, et al., 1993; Ovidio, et al., 2000). Most deployments depend on the size and the type of water body, the availability of water transportations like boats or different specific terrestrial principles such as triangulation. A boat is often used to locate the fish as it is a normal mobile system that is particularly effective for tracking movements and detecting habitat use by fish without recapture (Zydlewski, et al., 2001). An appropriate detecting range (1-5 m^2) should be tested until maximal signal strength (numerical indication in the receiver) is found (Ovidio, et al., 2000). At a close distance, hydrophones were more accurate than a Yagi, but the most accurate (<15 m) radio locations were done with a piece of coaxial cable (Niemela, et al., 1993).

A fixed or sentinel system can also be set up at predetermined locations along the bank or with buoys to observe a regular or periodical activity or migration of fishes. In small areas like streams, this system is used to record the movements past a single point. The tracking data is collected directly using a Yagi across a stream. For most occasions, the locations are calculated by telemetry triangulation in large waters. Variables such as the sampling sizes and the intervals were surveyed to improve the accuracy of triangulation in aquatic environments (Ovidio, et al., 2000). Fish locations were accurate to within 0.5 – 1.0 m when a close approach could be made using triangulation (David and Cross, 2001).

Substrate preference and habitat range

Since telemetry is a good tool to aid in the tracking of fish movements, it is often used to recognize home ranges by establishing frequency of occurrence over substrate types. Substrate types within home ranges may be defined as benthic fish habitats when the ranges are projected on the bottom. These preferred substrate types can also be identified as feeding, spawning and even resting sites if analyzed further.

Long term movements and habitat use

Radio tracking has facilitate seasonal movements and homing behavior of sturgeons to determine the geographic range (70-280 km) of post-spawning lake sturgeon, *Acipenser fulvescens* (Auer, 1999). The most striking feature of telemetry was the exact and directed nature of yearly movements of shortnose sturgeon *Acipenser brevirostrum* between four discrete areas in the Connecticut River. These areas were surveyed to determine summer feeding, spawning and over-wintering, but researchers did not find that individual fish returned to the same area annually. Since a series of locks and dams was constructed on the upper Mississippi River, the habitat use and movement of shovelnose sturgeon *Scaphirhynchus platorynchus* were believed to be impacted by low flow conditions (Hall et al 1991). The four months' telemetry tracking results indicated that the sturgeon tended to remain in the upper reaches of the rivers and these areas may be home ranges (Curtis et al., 1997).

Several studies of lake sturgeon movements have focused on the movable distances (Basset 1982). The fine scale movements were matched to available habitats using acoustic telemetry (Hay-Chmielewski 1987). The movements of lake sturgeon population from two fluvial lakes on the St. Lawrence River, Lac Saint-Luis and Lac Saint-Pierre were compared by Fortin et al 1993. Geographic ranges of movements were observed in the Sturgeon River and Lake Superior (Auer, 1999). A variety of habitats related to options for the protection and restoration of sturgeons were identified in a survey of sturgeon by researchers and managers (Beamesderfer and Farr, 1997). Substrate preference by juvenile lake sturgeon under laboratory conditions (Peake, 1999) and natural environments in northern Ontario rivers has been reported by Chiasson et al., (1997).

It is unclear whether fish are always sedentary and what types of habitat they use during winter. This problem has been largely ignored as the swimming ability was presumed to decrease and ice cover often made studies difficult. To overcome this, Brown et al (2001) took advantage of radio telemetry to track riverine brown trout *Salmo trutta*, white sucker *Catostomus commeersoni* and common carp *Cyprinus carpio*. These fishes were found to make longer movements as habitat were altered by increased water discharge and ice break up

Short term movements and habitat preference

The daily behavior of fish constitutes some basic and regular activities, including seeking food, resting, fleeing from predators and longer spontaneous mobility etc. All of these actions appear to be complicated and overlapping, but can be fundamentally divided into spatial (vertical and horizontal) mobility and temporal (diel) movements. It is possible to observe such activities over short period of several hours to days.

The external attachment of radio transmitters was used to track diel movements and to define close- and wide-range habitat of adult roach *Rutilus rutilus* for 14 days each time between 1994 and 1995 in the Spree, Germany (Baade and Fredrich, 1998). Stream-dwelling salmonids often showed strong site attachment to a territory or home range (Armstrong et al., 1994), but species varied in their responses. Low homing success of brook char *Salvelinus fontinalis* (157 – 215 mm) was shown by telemetry for 12 consecutive days between 29 July and 9 September 1998. The weakness in homing responses may have resulted from a tendency to settle rapidly in unfamiliar environments. There was also no evidence of differences between daytime and nighttime mobility (Bélanger and Rodríguez, 2001). A similar result of triploid grass carp *Ctenopharygodon idella* with surgically implanted radio transmitters showed that individual fish did not appear to take advantage of diel movements to forage in different areas. The home range (mean home range was 3234 ha and mean core use was 515 ha) was closely associated with aquatic vegetation. However, it was necessary to do this experiment after an acclimation period of 7 – 8 weeks following surgery (Chilton and Poach, 1997).

CHAPTER 3 MATERIAL AND METHODS

Study areas

All the study sites are given in Figure 1. The acoustic and benthic survey began in 2002, and represented part of the Northern Water System Research Project. The range covers two major prairie rivers in Manitoba and one long river and two little lakes in northern Canada. Fish telemetry was also implemented in part of the water systems during this period.

The Red River

The Red River is a single-channeled, meandering river with an 880 km long channel. It enters Manitoba from southern Minnesota/North Dakota. At Winnipeg, it joins the Assiniborne River before flowing into Lake Winnipeg. The Red River Basin (RRB) encompasses an area of about 290 000 km^2, including the Assiniboine River basin (163 000 km^2). About 16% of the Red River basin, excluding the Assiniboine basin, is located in Canada.

The Red River is a prairie river that has an average valley gradient of 0.0001 in Manitoba. The unique topography of the RRB contributes to a frequent flooding problem. Because the hydrologic system of the RRB is complex, the river is affected by many natural and human forces. Anthropogenic effects have greatly changed the aquatic ecological resources and the landscapes associated with the fish habitats in the river system. The environmental impact is watershed-wide, so the acoustic tracks of this study have covered the entire Red River located within Manitoba ranging from Emerson to the Lake Winnipeg inlet. Twenty three sections were surveyed between the early August, 2002 and the end of August, 2003. A benthic sampling section (11 sites) was selected around the Red River upstream of the Floodgates on May 16th 2003 (Figure 2).

The Winnipeg River

The Winnipeg River flows through the southeast corner of Manitoba, emptying into Lake Winnipeg. The Winnipeg River drains more than 125,000 km^2 within

Figure 1. Study areas in Canadian water systems

There are five freshwater systems (Red River, Winnipeg River, Mackenzie River, Chitty Lake and Wormy Lake) were selected for acoustic tracking, and benthic sampling. Three of these also collected data on fish movements. Base map from http://geogratis.cgdi.gc.ca/nationalatlas/e_basemaps.html

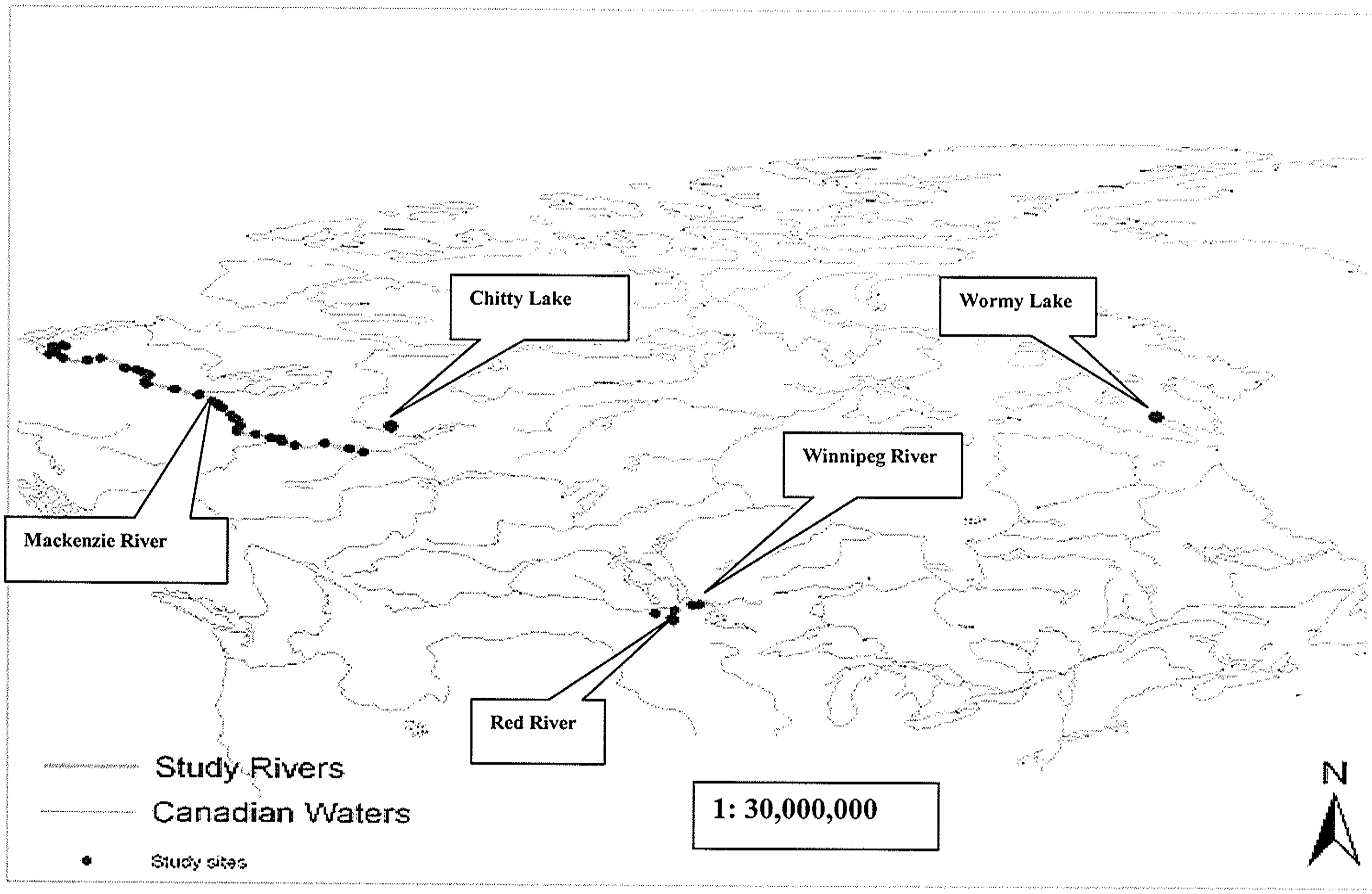

Chitty Lake
Wormy Lake
Mackenzie River
Winnipeg River
Red River
Study Rivers
Canadian Waters
Study sites
1: 30,000,000
N

Figure 2. Survey areas of the Red River in Manitoba

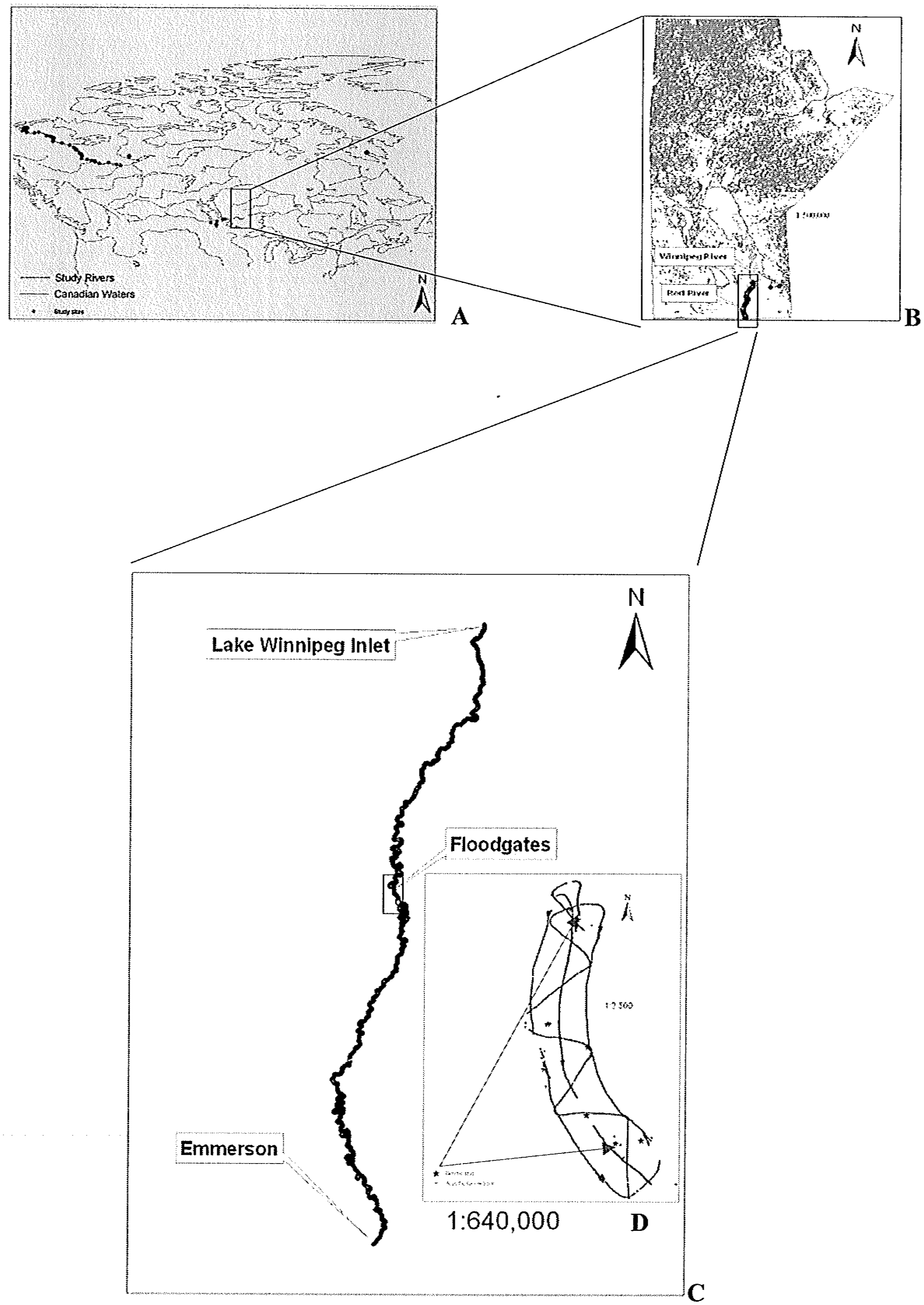
Tracks along the Red River where acoustic data was collected with the QTC VIEW Series V. Note that the entire river from the USA/Canada border (Emerson) was mapped. The inset shows detail on one transects along the river upstream of the Floodgates. Arrows indicate the general locations where the benthic samples (star) were collected. Base map from NTS base maps of NRCAN.

A: From Figure 1 (P25)

B: Two study areas in Manitoba

C: Acoustic and benthic surveys in the Red River

D: Acoustic and benthic survey on the Red River upstream of the Floodgates



Study Rivers
Canadian Waters
N
A
N
Winnipeg River
Red River
B
N
Lake Winnipeg Inlet
Floodgates
Emmerson
1:640,000
D
C

northwestern Ontario, northern Minnesota and southeastern Manitoba. Six dams were built along the river and it is generally believed that hydroelectric development has been having a major impact on the sturgeon population by blocking the migrations of large fish. There are several areas such as Pigeon River, Slave Falls, Seven Sisters, Numao Lake and Pointe Du Bois where lake sturgeons are found in the river. Numao Lake and Seven Sisters were chosen as two sites to study in detail as the former is run-of-the-river and the latter is markedly altered following the building of the Seven Sisters dam. Numao Lake was surveyed for acoustic data and sediment samples (39) on October 7th 2003. Seven Sisters was done for three acoustic datasets (October 10th 2002, July 24th 2004, and June 8th 2005), for a benthic survey (June 8th 2005) and a telemetry was studied and initiated on July, 24th 2004 (Figure 3).

<u>The Mackenzie River</u>

The Mackenzie River is the longest river in Canada covering a distance of approximately 1800 km. The river begins at Great Slave Lake in the Northwest Territories and flows north before emptying into the Arctic Ocean. It's most important tributaries are the Liard, or Mountain River, the Peel River, and the Great Bear River. The Mackenzie River system totals almost 4,200 kilometers and its watershed, 1.8 million square kilometers in size, drains one-fifth of the country of Canada. Along its course, it discharges 306 cubic kilometers of water per year (including 100 million tons of sediment), depositing its heavy burden of sand and silt into the channels, lakes and sandbars of the vast Mackenzie Delta. The Mackenzie River is navigable from June to October and then it eventually freezes over. The replenishment of water and nutrients in the lakes of this system are dependent on river flooding, which is largely controlled by ice-jamming on the Mackenzie River during spring breakup.

The Mackenzie remains one of the most undeveloped, sparsely populated across in Canada, with significant specific wildlife/resources, and other natural non-renewable resources, especially in the delta region. Twenty six sections were assessed between June 19th and September 7th 2003 (Figure 4), where 1 – 6 benthic samples were collected on the reach of the river.

Figure 3. Survey areas of the Winnipeg River in Manitoba

Two sections of Numao Lake and Seven Sisters within the Winnipeg River were chosen for acoustic and benthic surveys. The inset shows detail on Numao Lake and Seven Sisters. The arrows indicate the general locations (big star points) where the benthic samples were collected. Note that telemetry was performed for the movement of lake sturgeon at Seven Sisters. Base map from NTS base maps of NRCAN.

A: From Figure 1 (P25)

B: Two study areas in Manitoba

C: Survey of two sections in the Winnipeg River

D: Acoustic and benthic surveys on Numao Lake, the Winnipeg River

E: Acoustic and benthic survey on Seven Sisters, the Winnipeg River

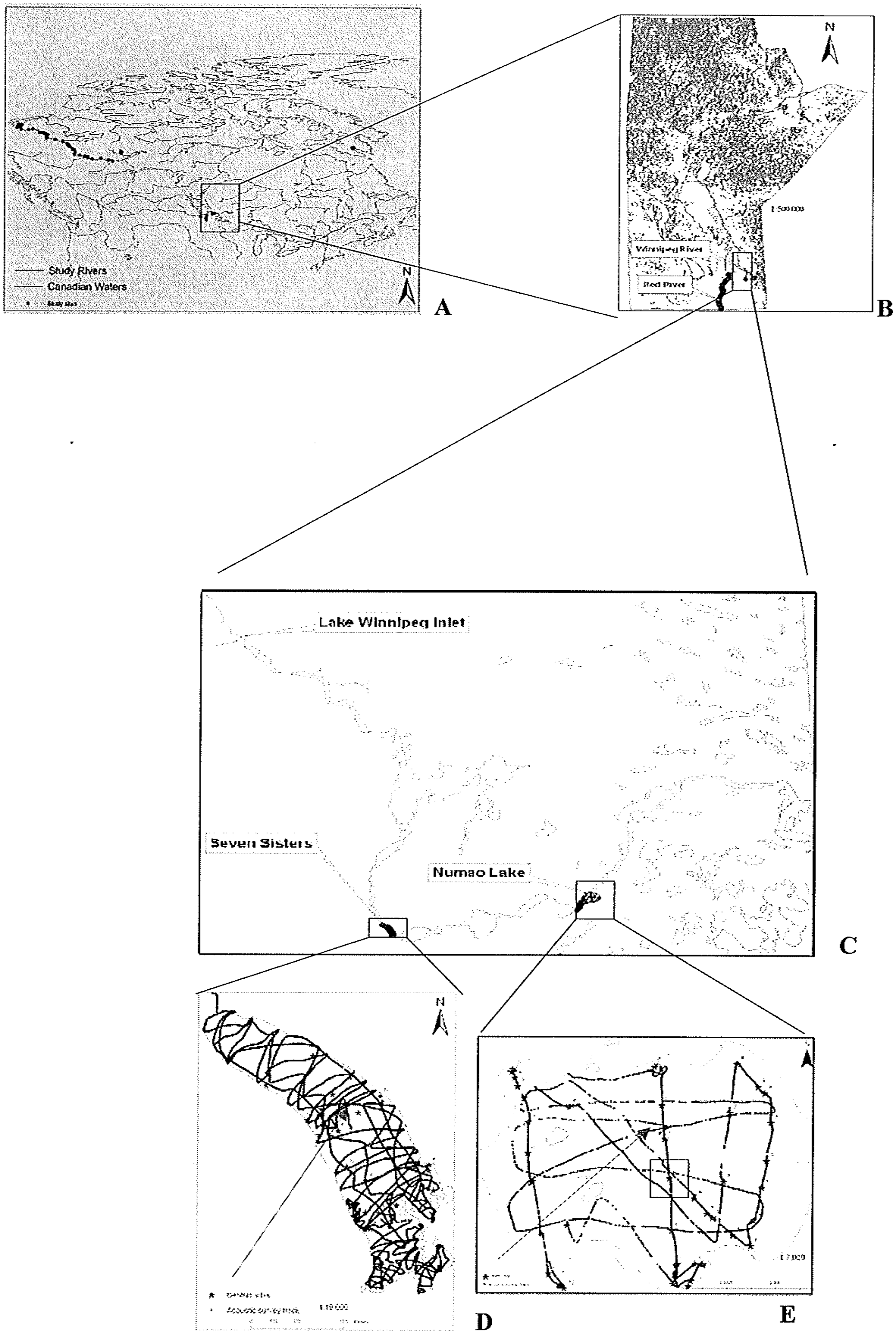

Study Rivers
Canadian Waters
N
A
N
Winnipeg River
Red River
B
Lake Winnipeg Inlet
Seven Sisters
Numao Lake
C
N
D
E

Figure 4. Survey areas of the Mackenzie River

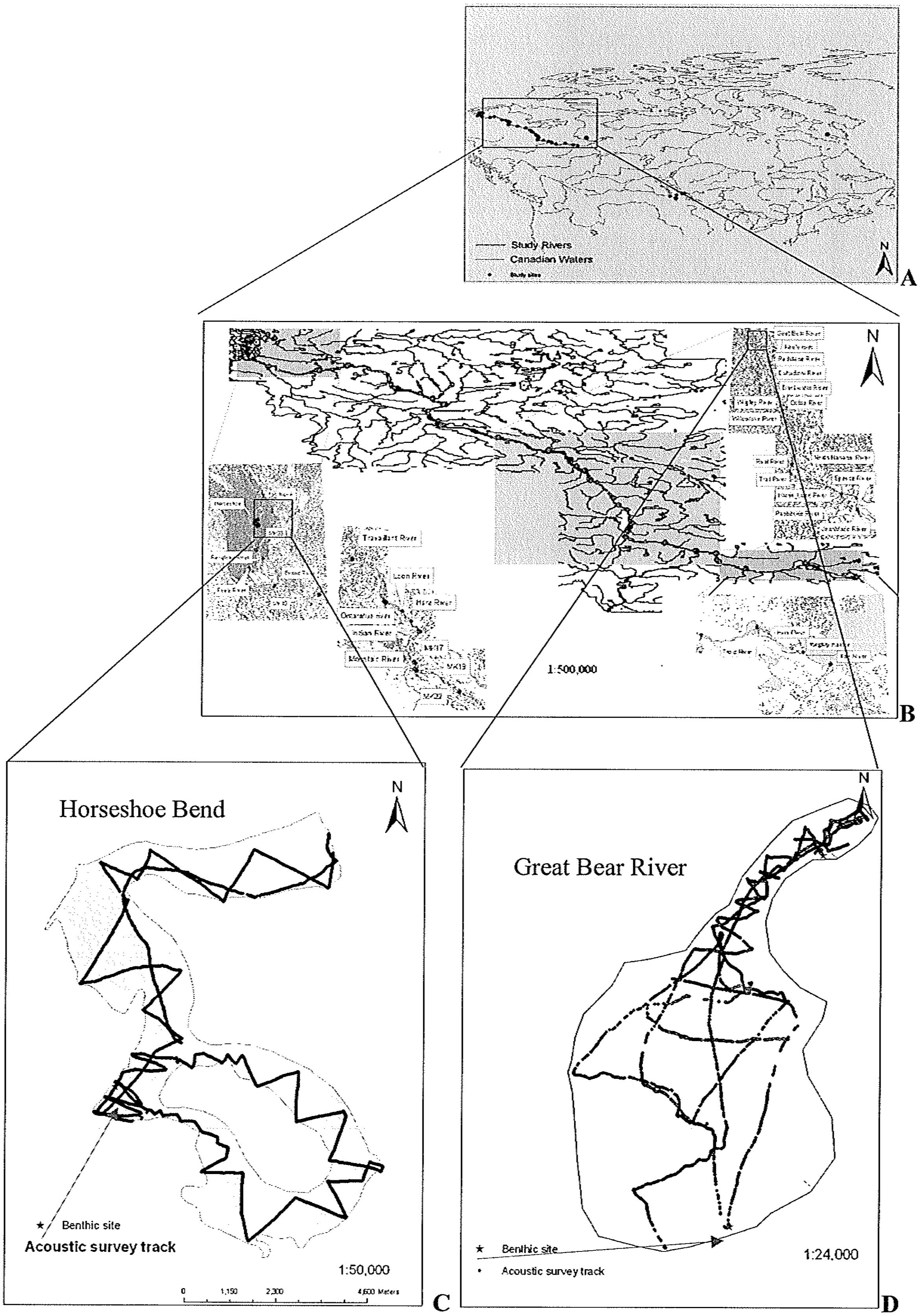
There are survey locations along the Mackenzie River where detailed acoustic data and benthic samples were collected. Two of the sections along the river, Horseshoe Bend and Great Bear River are enlarged. Base map from NTS base maps of NRCAN.

A: From Figure 1 (P25)

B: Survey of four sections in the Mackenzie River

D: Acoustic and benthic surveys on Horseshoe Bend, the Mackenzie River

E: Acoustic and benthic survey on Great Bear River, the Mackenzie River


Study Rivers
Canadian Waters
N
A
N
1:500,000
B
Horseshoe Bend
N
Benthic site
Acoustic survey track
1:50,000
0
1,150
2,300
4,600 Meters
C
Great Bear River
N
Benthic site
Acoustic survey track
1:24,000
D

Chitty Lake

Chitty Lake lies about 28 kilometers north of Yellowknife, Northwest Territories. The geographic location is about 62°42'50''N and 114°07'55W. It is long and narrow with its major axis running north and south. Two deep holes are distributed in the north and south. The basin is surrounded by low, sparsely wooded hills typical of the northern Precambian Shield, having a surface area of 305 ha. There is much exposed granite rock, but also some overlying sedimentary rock in the catchments basin that probably increases the nutrient supply. Chitty Lake is one of the four lakes (Chitty, Drygeese, Baptiste and Alexie) where the effects of different levels of exploitation on lake trout and whitefish populations were studied during the period 1972-75 (Healy, 1975). The trophic feeding structure and the movement patterns of the two species relative to depth and substrate were studied in Chitty Lake. An acoustic survey (June 18th 2003 and April 22nd 2005), the telemetry of 17 lake trout (September 16th -19th 2004) and 34 benthic samples (June 18th 2003 and April 22nd 2005) were required to cover the whole lake (Figure 5).

Wormy Lake

Wormy Lake is one of a cluster of lakes near Iqaluit in the eastern part of Nunavut. Its geographic location lies at 63°41'21''N and 68°22'32W. It is completely undisturbed with little knowledge available about its lake morphometry. Performing an acoustic track, benthic samples (100 sites) and Arctic char telemetry in this lake will provide a full study of the relationship of the bathymetry, the substrate types and the fish movement from July 13th -15th 2004 (Figure 6).

Figure 5. Survey area of Chitty Lake

There are survey locations within Chitty Lake where detailed acoustic data and benthic samples were collected. Note that telemetry was performed for the movement of lake trout at this lake. Base map from NTS base maps of NRCAN

A: From Figure 1 (P25)

B: Acoustic and benthic survey of Chitty Lake

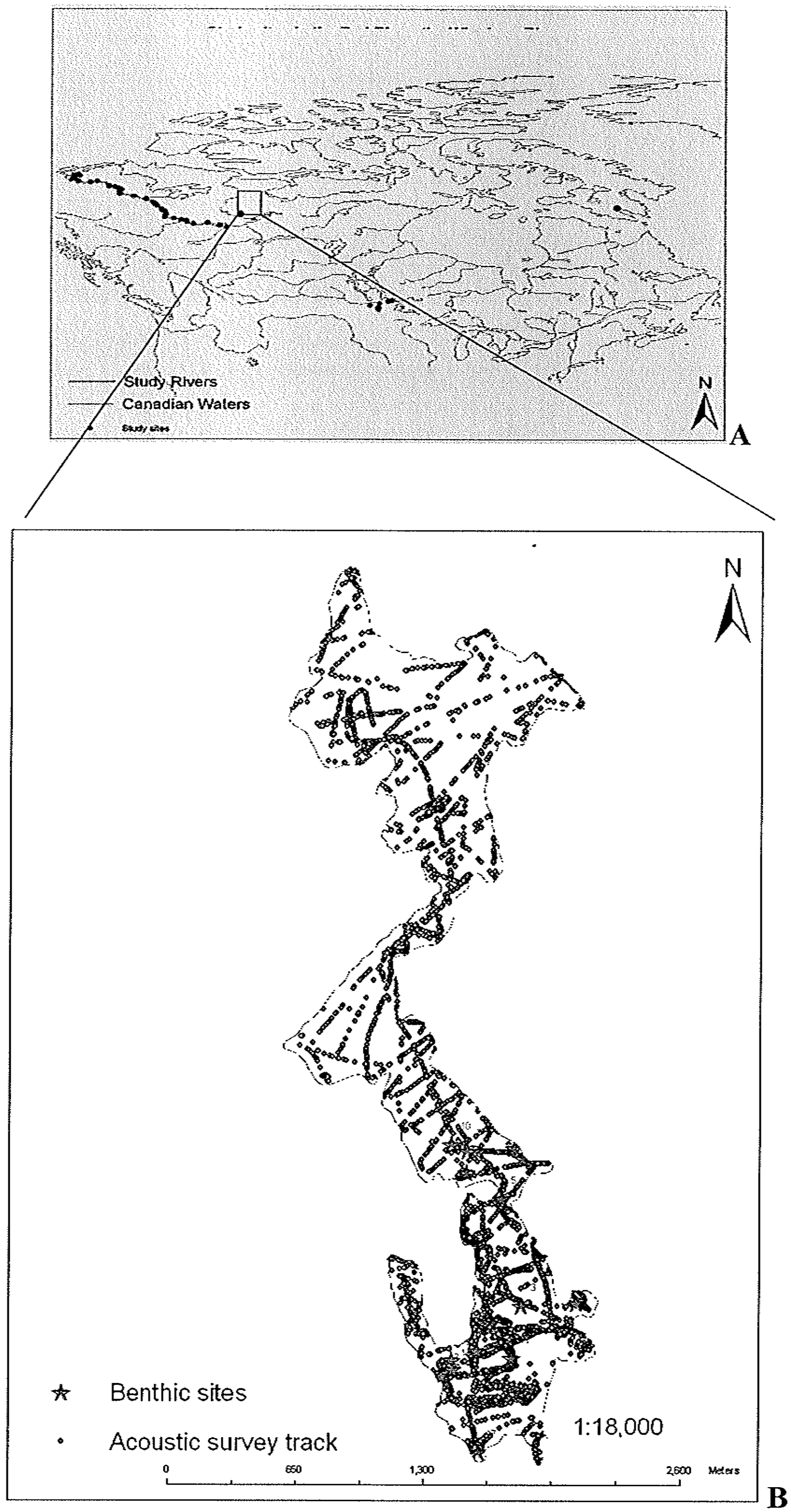
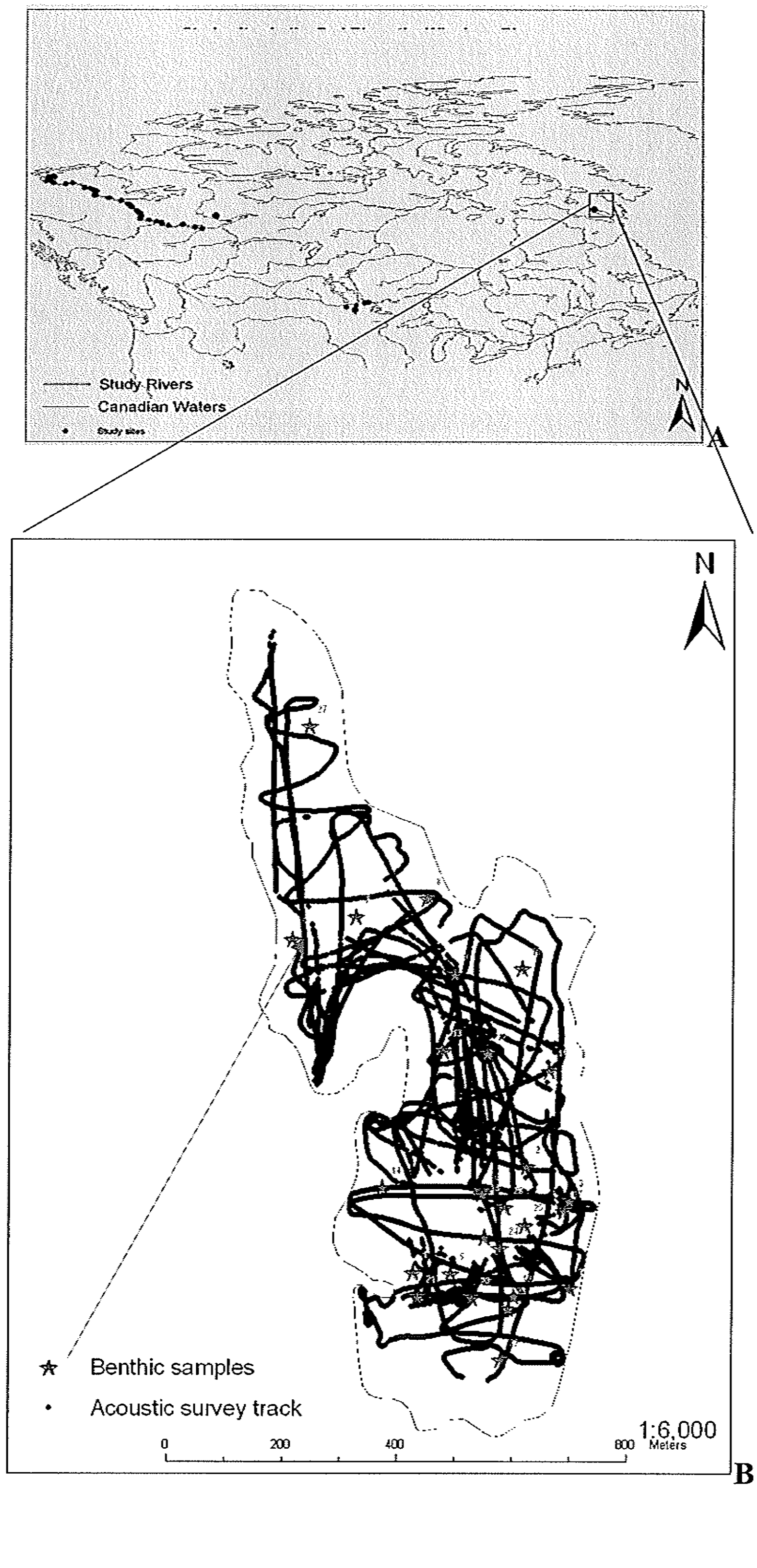

Study Rivers
Canadian Waters
N
A
N
Benthic sites
Acoustic survey track
1:18,000
0
650
1,300
2,600
Meters
B

Figure 6. Survey area of Wormy Lake

There are survey locations within Wormy Lake where detailed acoustic data and benthic samples were collected. Note that telemetry was performed for the movement of Arctic char at this lake. Base map from NTS base maps of NRCAN.

A: From Figure 1 (P25)

B: Acoustic and benthic survey of Wormy Lake


Study Rivers
Canadian Waters
Study sites
N
A
N
Benthic samples
Acoustic survey track
1:6,000
0
200
400
800
Meters
B

Data/Sample collection

Acoustic data

Work principle of the QTC5 system

The QTC VIEW Series V (QTC5) works as follows: 1) a sounder transmits an echo sounder signal through a transducer and the return signal is captured by the transducer; 2) the captured echoes are digitized in a sounder interface module; 3) the digitized echoes from several consecutive returns are averaged using the multiple algorithms of the QTC VIEW software in a computer and an effective waveform representing the bed surface and immediate subsurface is formed in a specific data format; 4) each effective waveform is synchronized with a pair of longitude and latitude input from a differential GPS. The operational Input/Output flow **is** summarized in Figure 7.

Collection of acoustic data

Acoustic data were collected using a boat mounted QTC5 linked to a GPS (Figure 8). Once the system setup was completed on the field, three configuration steps needed to be done before the positions were logged continuously along with the traces and the depths: set the configuration parameters (Table 1), measured the blanking depth and the pulse length, and synchronized the time between a data acquisition PC and a GPS. Note that any alteration of the parameters would result in changes to the nature of the echoes that would affect the classification.

An acoustic survey must be performed at a steady speed (recommended as 7.6 - 9.5 km/hr) with lengthwise lines along the water flow orientation crossed with zigzag lines to verify specific signals in order to prevent measuring errors and interpolating bias.

Figure 7. Operational Input/Output flow of QTC VIEW Series V
Note that a sounder is connected to a transducer which is linked by one cable end of a sounder interface module. The other end of the module is connected to a computer installed with QTC VIEW software which also receives data from a differential GPS.

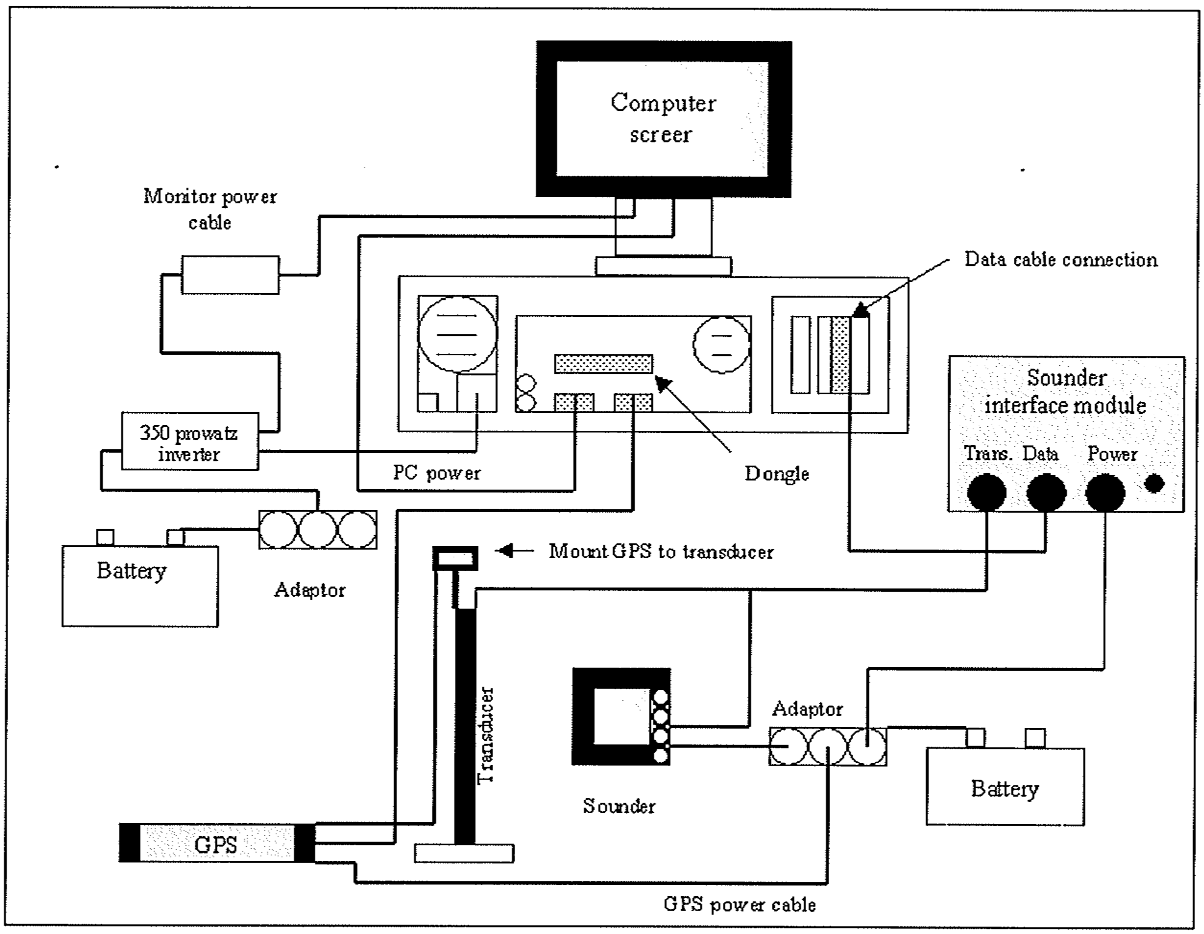

Computer
screer
Monitor power
cable
Data cable connection
350 prowatz
inverter
PC power
Dongle
Sounder
interface module
Trans. Data
Power
Battery
Adaptor
Mount GPS to transducer
Transducer
Adaptor
Sounder
Battery
GPS
GPS power cable

Figure 8. QTC5 setup and performance

A: Installation of the QTC5 system which includes a computer installed with the QTC VIEW software, a sounder, a sounder interface module, a transducer, a differential GPS, batteries and other accessories (at Numao Lake, the Winnipeg River).

B: The tracking survey of installed the QTC5 at Renleng River, a tributary of the Mackenzie River

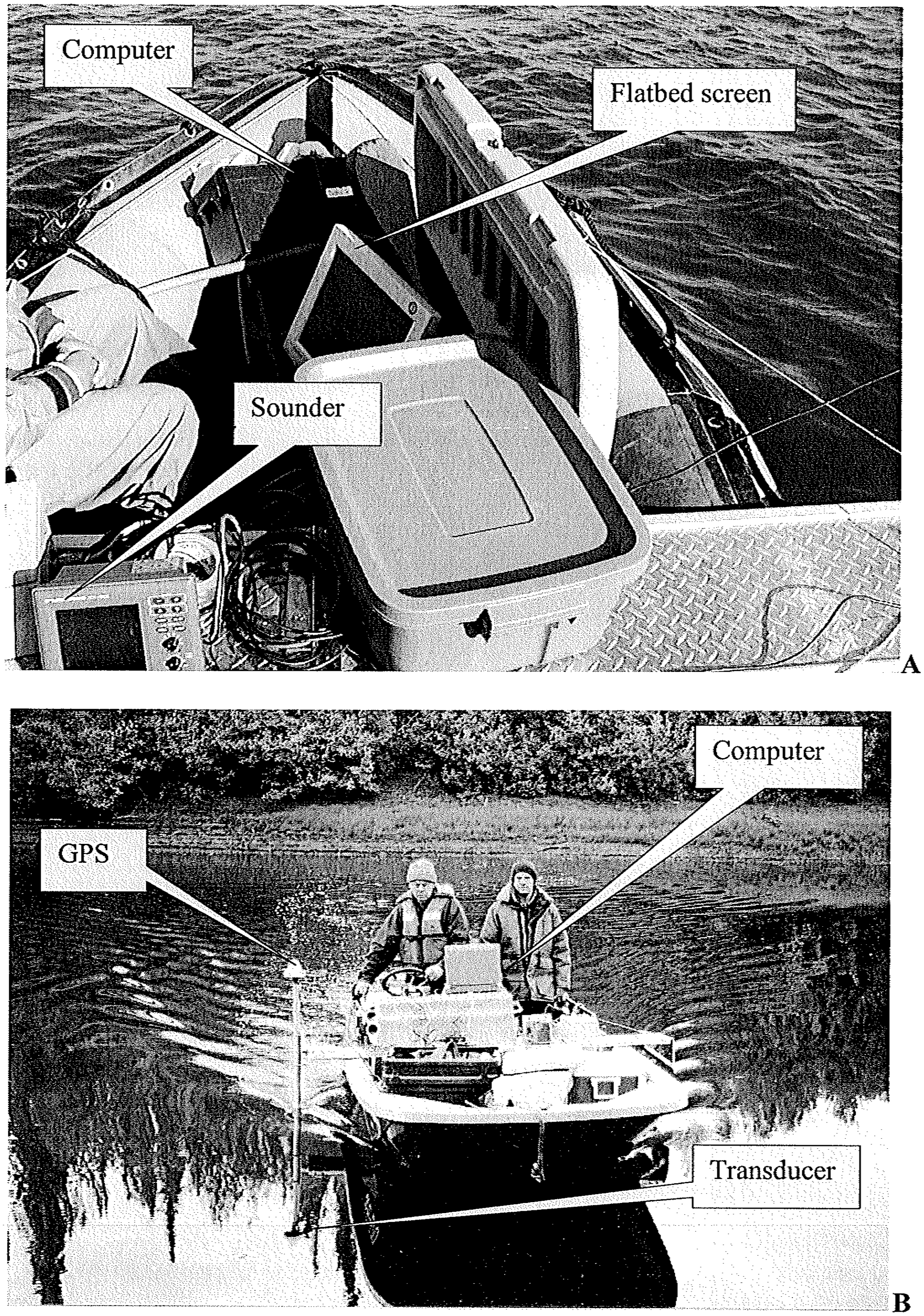

Computer
Flatbed screen
Sounder
A
Computer
GPS
Transducer
B

Table 1 Survey base setting for the echo sounder and the QTC VIEW™ series V

	Parameter	Settings
Echo sounder	Pulse duration	360
	Beam width	24°
	Transmit power	150
	Range	40m
	Ping rate	5/s
QTC VIEW	Base gain	54 dB
	Reference depth	60m
	Maximum	2000

Benthic samples

Sediment sampling was conducted from a stationary boat with the QTC5 collecting the acoustic signal over a specific location. The sample sites were selected to ensure that most of the substrate types were collected and were distributed along the lengthwise lines and zigzag lines. Each site was recorded for a water depth and a geographic position. The transects were set across the depth gradient in a lake or river, were shifted from the shallow areas to the deeper areas. The sample sites in rivers were determined based on low to high current flow.

The acoustic data collection and the benthic samples were supplemented with visual observations and bottom probing at some of the sample sites. The field survey sequence was followed with GPS positioning, grab sampling, and pole probing/visual observations. This means that each site was located by the differential GPS; a Ponar grab was dropped at the specific site to obtain sediment samples; the bottom floors at some sites, however, were probed and/or visualized if possible. Each sample was described, i.e. silt, clay, gravel etc., then placed in a plastic bag and kept frozen until it was tested in the lab.

Telemetry data

Tagging

All lake sturgeons to be tagged were cultured and tags were surgically implanted to fish at the animal holding facility of the University of Manitoba. These fish were the progeny of stocks from the Winnipeg River and ranged in age from 3 – 16 years when stocked. Lake trout and Arctic char were captured in the water body where the movement studies took place. Information on all of the fish fitted with tags is given in Table 2:

1. *Surgical implantation*

The fish were immersed in a tub containing the anesthetic (MS-222) for approximately 5 minutes depending on fish condition and size before tagging. When the fish were fully anaesthetized, showing no reaction to external stimuli, they were placed on a sterile surface for the surgical implant procedure after their fork length and body weight were measured.

Table 2 Fish tagging and release status

Surgery date	Species	Sonar tag ID	Fish weight (g)	Fork length (cm)	Pit tag number	Floy tag number	Sonar tag type	Tag initiation date	Fish release date	Fish release location
7/5/2004	Lake Sturgeon	118	3372	71.4	133534357A	1529	V16-4H-Ro4K	7/5/2004	26/7/2004	Seven Sisters
15/5/2004	Lake Sturgeon	120	2714	68.2	122556637A	1577	V16-4H-Ro4K	15/5/2004	26/7/2004	Seven Sisters
15/5/2004	Lake Sturgeon	124	5789	91	122564680A	1526	V16-4H-Ro4K	15/5/2004	26/7/2004	Seven Sisters
15/5/2004	Lake Sturgeon	58	944	49.3	122937330A	1552	V8SC-2H-R256	5/13/2004	26/7/2004	Seven Sisters
25/5/2004	Lake Sturgeon	163	3640	75.5	122475340A	1528	V16-4H-Ro4K	25/5/2004	26/7/2004	Seven Sisters
25/5/2004	Lake Sturgeon	165	5382	83.4	122779564A	1520	V16-4H-Ro4K	25/5/2004	26/7/2004	Seven Sisters
25/5/2004	Lake Sturgeon	167	6721	91.6	134479556A	1524	V16-4H-Ro4K	25/5/2004	26/7/2004	Seven Sisters
25/5/2004	Lake Sturgeon	170	5620	87.8	133533113A	1523	V16-4H-Ro4K	25/5/2004	26/7/2004	Seven Sisters
27/5/2004	Lake Sturgeon	173	8693	93.3	134725210A	1521	V16-4H-Ro4K	27/5/2004	26/7/2004	Seven Sisters
27/5/2004	Lake Sturgeon	174	2728	67.2	122564186A	1525	V16-4H-Ro4K	27/5/2004	26/7/2004	Seven Sisters
27/5/2004	Lake Sturgeon	176	5040	80.2	122567464A	1575	V16-4H-Ro4K	27/5/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	177	2201	64.8	123427174A	1542	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	178	2320	68.4	013*833*617	1571	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	179	2166	63.1	135133555A	1537	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	181	2596	65.4	123463592A	1541	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	183	1430	54.9	134468556A	1547	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	184	2447	65.8	133644521A	1530	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
3/6/2004	Lake Sturgeon	187	1532	54.2	134671551A	1532	V16-4H-Ro4K	3/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	164	1377	33.3	134453372A	1564	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	166	1663	60.3	134976496A	1556	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	168	1209	50.8	133624180A	1549	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	171	1131	52.3	133745185A	1574	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	175	1253	52.4	133573564A	1531	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	180	1139	52.3	133615586A	1534	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	182	1323	53.3	133648144A	1573	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	185	1315	53.1	133546654A	1536	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	186	1284	53.2	135135374A	1545	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	188	1217	52.7	133959164A	1569	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	189	1336	54.6	133957154A	1550	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
4/6/2004	Lake Sturgeon	191	1354	53.9	134422696A	1538	V16-4H-Ro4K	4/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	193	1064	48.6	135122254A	1572	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	194	1466	59.2	133554754A	1558	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	196	1081	50.6	133629311A	1567	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	198	1114	52.8	133938693A	1543	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	200	1071	50.4	135121295A	1570	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
5/6/2004	Lake Sturgeon	201	1098	48.9	133531755A	1557	V16-4H-Ro4K	5/6/2004	26/7/2004	Seven Sisters
7/6/2004	Lake Sturgeon	203	2167	58.2	123311466A	1565	V16-4H-Ro4K	7/6/2004	26/7/2004	Seven Sisters
7/6/2004	Lake Sturgeon	204	1271	52.1	135116566A	1561	V16-4H-Ro4K	7/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	24	1147	51.6	142422532A	1566	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	29	1310	51.4	142252756A	1548	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	32	1040	49.8	142164350A	1539	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	46	1095	49.9	142165392A	1546	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	50	1119	50.2	142433335A	1533	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	59	1135	50.7	142255467A	1544	V8SC-2H-R256	10/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	31	980	49.2	142776754A	1559	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters

13/6/2004	Lake Sturgeon	34	1070	50.3	142855577A	1563	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	36	1031	49.8	142773166A	1562	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	40	1010	50.4	142811625A	1540	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	44	1036	50.5	142252317A	1568	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	47	1038	50.6	142752325A	1560	V8SC-2H-R256	11/6/2004	26/7/2004	Seven Sisters
13/6/2004	Lake Sturgeon	205	24449	127.4	142271663A	1519	V16-4H-Ro4K	13/6/2004	26/7/2004	Seven Sisters
16/6/2004	Lake Sturgeon	35	1308	52.1	142855683A	1600	V8SC-2H-R256	15/6/2004	26/7/2004	Seven Sisters
16/6/2004	Lake Sturgeon	37	1095	50.5	142809321A	1598	V8SC-2H-R256	15/6/2004	26/7/2004	Seven Sisters
16/6/2004	Lake Sturgeon	41	1232	51.1	142165657A	1597	V8SC-2H-R256	15/6/2004	26/7/2004	Seven Sisters
16/6/2004	Lake Sturgeon	43	1090	49.8	142256223A	1551	V8SC-2H-R256	15/6/2004	26/7/2004	Seven Sisters
16/6/2004	Lake Sturgeon	53	1094	52.7	142812121A	1599	V8SC-2H-R256	15/6/2004	26/7/2004	Seven Sisters
15/09/2004	Lake trout	85, 86	3100	64.1		FM4801	Temp, pressure, loc	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	77, 78	2150	56		FM4802	Temp, pressure, loc	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	70	1950	56.5		FM4804	Pressure, location	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	87, 88	1900	52.5		FM4805	Temp, pressure, loc	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	224	1240	48.9		FM4806	Location	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	69	1900	56		FM4807	Pressure, location	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	225	1500	50.6		FM4808	Location	15/09/2004	15/09/2004	Chitty Lake
15/09/2004	Lake trout	220	1250	47		FM4810	Location	15/09/2004	15/09/2004	Chitty Lake
16/09/2004	Lake trout	81, 82	2150	57		FM4847	Temp, pressure, loc	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	68	1750	53.5		FM4846	Pressure, location	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	214	1250	46.5		FM4835	Location	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	211	1150	47.8		FM4834	Location	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	215	1100	47.6		FM4833	Location	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	75, 76	2550	58.2		FM4832	Temp, pressure, loc	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	65	2100	55.6		FM4831	Pressure, location	16/09/2004	16/09/2004	Chitty Lake
16/09/2004	Lake trout	212	1250	48.5		FM4826	Location	16/09/2004	16/09/2004	Chitty Lake
18/09/2004	Lake trout	79, 80	2300	61		FM4821	Temp, pressure, loc	18/09/2004	18/09/2004	Chitty Lake
13/7/2004	Arctic char	90	1850	55.5			V9	15/7/2004	15/7/2004	Wormy Lake
13/7/2004	Arctic char	406	500	39.5			V7			Wormy Lake
14/7/2004	Arctic char	406	95	21			V7	15/7/2004	15/7/2004	Wormy Lake
14/7/2004	Arctic char	425	100	22.4			V7			Wormy Lake
14/7/2004	Arctic char	91	2200	62.5			V9	15/7/2004	15/7/2004	Wormy Lake
14/7/2004	Arctic char	94	1450	53			V9	15/7/2004	15/7/2004	Wormy Lake
14/7/2004	Arctic char	405	150	26.2			V7			Wormy Lake
14/7/2004	Arctic char	404	140	25			V7			Wormy Lake
15/7/2004	Arctic char	405	100	24.3			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	404	100	23			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	403	725	42			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	402	525	39.5			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	401	250	33			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	93	950	45.5			V9	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	400	700	40.9			V7	15/7/2004	15/7/2004	Wormy Lake
15/7/2004	Arctic char	415	460	36.8			V7			Wormy Lake
15/7/2004	Arctic char	414	445	35.8			V7			Wormy Lake
15/7/2004	Arctic char	413	110	22.4			V7	15/7/2004	15/7/2004	Wormy Lake

The anaesthetized fish were tagged with a 69 KHz coded transmitters manufactured by VEMCO. Each tag was configured to transmit a pulse at random time intervals with a delay of between 20 and 69 seconds before the next signal. The transmitters are cylindrical in shape with rounded edges. Each weighs 25.5 grams and measures 70 mm in length and 15 mm in diameter.

After the fish had surgical implantations, all the fish were allowed to recover for a period of 3-4 weeks (lake sturgeon) or while lake trout and Arctic char were held in a confined natural area for at least five hours prior to release.

2. *Identification tag*

Lake sturgeons were tagged with a PIT (Passive Integrated Transponder) under the fourth dorsal scute after the fork length and the body weight were recorded. Fish were also fitted with individually numbered floy tags (all four species). The floy tags were inserted at the base of the dorsal fin. The PIT and the floy tags served two purposes, i.e. for the long term identification of an individual and for the assessment of external tag loss.

Tracking

VEMCO VR2 receivers were used to monitor the movements of fish. The VR2 was designed to identify the VEMCO coded transmitters and was set to record 69 kHz frequency signals. It recorded the date and time of the valid detections of the transmitter codes. The VR2 is cylindrically shaped measuring 205 mm in length and 60 mm in diameter. One end of the receiver accommodates a single D cell battery while a hydrophone is situated on the other end. Data is stored in a nonvolatile Flash Memory until the memory is full. Approximately 300,000 valid detections can be stored in the memory.

The VR2 mooring unit was a concrete pad used as an anchor and a stand for the receiver. One end of the receiver was bolted to the pad while the other end was attached to a line to which a float or line was used to hold the receiver vertically. The receiver was lowered into the water with a chain attached to the pad and positioned vertically with the hydrophone pointing towards the surface. Once every two months or so, data was retrieved from the receiver through a communication probe inserted in a receptacle located near the hydrophone. Simultaneously, the communication probe was connected to a laptop computer and downloaded the data into the VEMCO VR2 PC software.

Data/sample analysis

Two kinds of data sources were collected: One was auto-acquisition data from the acoustic and the telemetric survey and the other was data acquired manually from samples collected at specific sites. These data were either raw data without direct interpretations or without physically mixed components. In order to compare the two data sets, data processing was required in which the different forms of data were converted into compatible formats before they were integrated with each other on a GIS platform.

<u>Classifying acoustic data</u>

Any entire acoustic response from the QTC VIEW™ is a complicated waveform that is described in 166 feature variables. Some of the features are based on the echo shape and others on the spectral characteristics. The echo shape was analyzed to be rich in sediment information. The QTC IMPACT™ was applied to process the QTC VIEW™ echo features and finally to extract the sediment patterns through the 'Cluster' based on the PCA and K-means embedded in the QTC IMPACT™ software.

The whole process was parsed into three steps: converting raw data to full feature vector (FFV) data; removing poor quality FFV data; classifying the catalogue data. The final step for acoustic data classification by splitting this data was to ensure the acoustic data was correlated with benthic samples. CPI (Cluster Performance Index) rate is comparatively recognized for the stop split process, which is the ratio of the distance between clusters centers and extent of the cluster in Q-space (QTC IMPACT User Guide, 2002), but is not always absolute in practice. It was very important that the benthic sedimentary information be matched for an objective determination of the optimal number of classes.

<u>Sorting benthic samples</u>

The organization of the sediment samples required several steps. First, it was important to keep and to refer to the field descriptive records about the benthic samples and the bottom types. This method is referred to as "Visual Classification". It was useful for the observation of the bedrock, hard clay surfaces, boulders with bigger cobbles, and compact sandy patches from the probing and/or visual information. Second, if benthic samples were available, the major sediments of each sample were subjected to a preliminary examination and the approximate percentages determined visually. Because an initial benthic sample consisted of unconsolidated sediments, which were mixed up with mineral, suspended, clumped, or shaped-organic (mostly benthic plants) materials, in a lab, it had to be prepared for sorting by water dispersion in order to separate each component of the sediments.

Samples containing mostly clumped organic materials required that a small amount of the sample be separated in a Petri dish in order to identify the components with the aid of a binocular microscope. Except for well-defined mineral grain sizes, the suspended material was examined for the components that remained in suspension in three sizes (small, medium and large) after five minutes. In a similar way, the clumped materials referred to very fine organic materials that settled to the bottom and the shaped organic materials were identified as benthic plant and animal remains. Three observers the initial classification independently and as the consistency improved the descriptive classification was checked and verified.

This "Visual Classification" had the advantage of allowing a rapid identification of substrates on freshly collected material. However, it was less useful for the calculation of the average particle sizes of a substrate type and for the subsequent interpolation of continuous substrate patterns as compared to the results from the sieving method.

A third sediment classification scheme used here was sieving which separates mineral grain-sizes so that the average substrate size can be correlated with the acoustic classes. According to this classification scheme, a series of sedimentary particles were sieved into silt-clay (<0.063 mm), sand (0.063-2 mm), gravel (2-16 mm), pebble (16-64 mm), cobble (64-256 mm), and boulder (>256mm) in a sample from one grab at each site (Figure 9). The procedure is outlined below:

Initial particle size separation

a. 100 ml aliquot from a total sample at one site is placed in a beaker.
b. Sample is placed into a 400 ml plastic beaker with a label (data, number, and location) until it thawed.
c. Water is added along with a dispersant (Calgon) to aid separation.
d. The solution is mixed with a glass rod.
e. Sit in a freezer overnight.
f. The sample is thawed.
g. It is mixed again after thawing.
h. Repeat Step e and Step f to ensure there are no clumps.
i. Separate the silt and clay particles from the complete mixed solution using a sieve of 63 micro millimeters.
j. Collect the silt and clay passing through the sieve in a separate container.
k. Place the sediment left in the sieve in a pyrite beaker

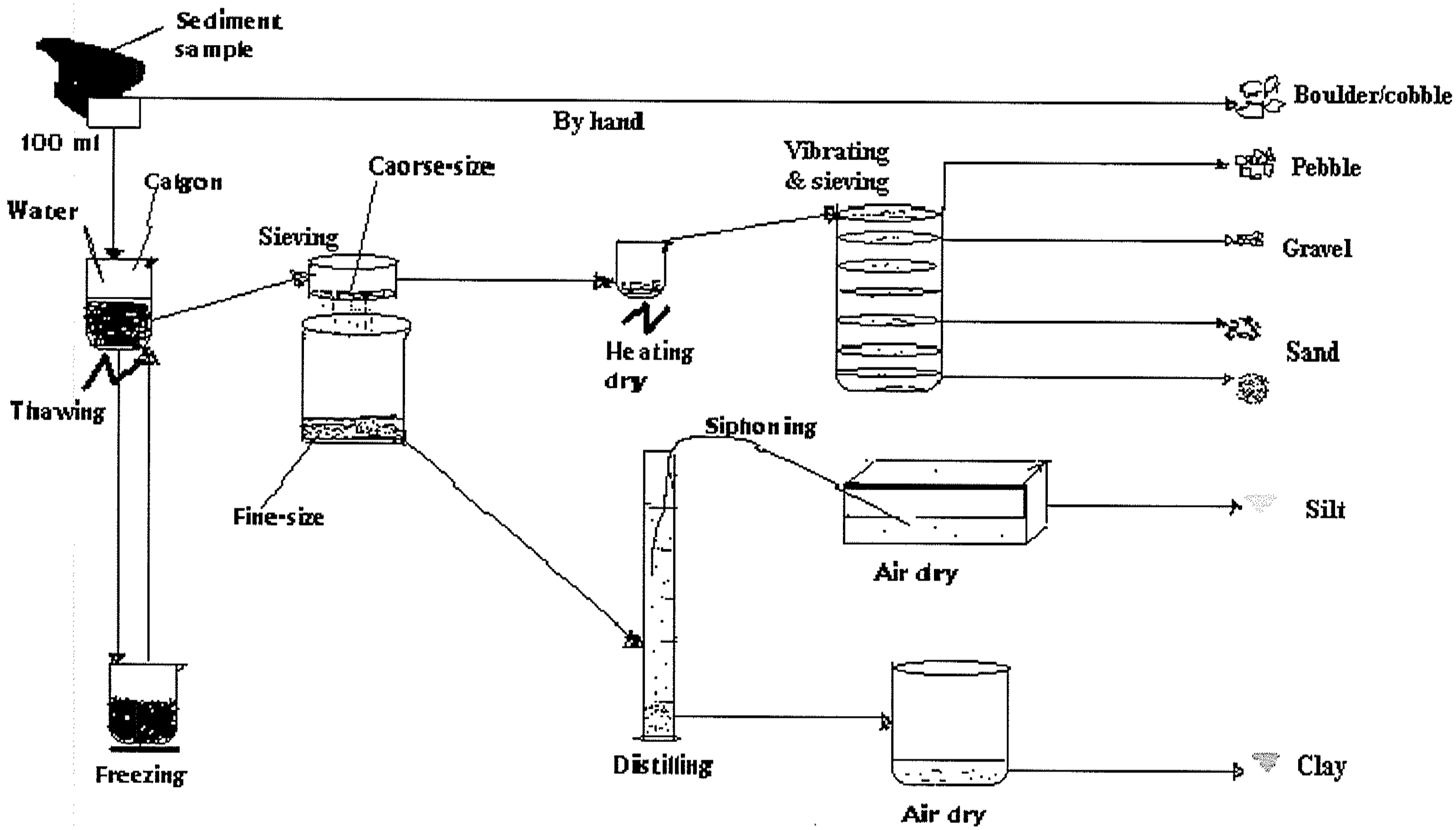
Larger particle size sieving (>63 micro millimeter)

a. Allow the sample in the pyrite to completely dry in the oven.
b. Break up any chunks formed during the drying process with a pestle and mortar.
c. Weigh the total sample and place it in a series of sieves ranging from 16 mm to 0.0625 mm.
d. Allow shaking the sample 10 minutes in a T-tap shaker.
e. Weigh and record the material in each sieve.

Fine particle size (<63 micro millimeter) settlement

a. Place the silt/clay sample into a 4000 ml graduated cylinder.
b. Add water to the cylinder to make a total of 4000 ml solution.
c. Stir the solution thoroughly and allow to settle for 6 minutes and 30 seconds
d. Siphon the supernatant (water and suspended particles smaller than 63 micron) until a volume of 1000 ml is reached and save the 3000 ml.
e. Repeat two other times from Step b to Step e.
f. Dry the siphoned supernatant (7000 ml) and the residue solution (1000ml) and weigh the dried materials.

Figure 9. Diagram of the procedures to separate the homogeneous components of a benthic sample


Sediment sample
100 ml
By hand
Boulder/cobble
Water
Calgon
Thawing
Freezing
Caorse-size
Sieving
Fine-size
Heating dry
Vibrating & sieving
Pebble
Gravel
Sand
Siphoning
Air dry
Silt
Distilling
Air dry
Clay

This procedure gave accurate data for the weight percentages of each grain size as well as a quick understanding to the field site concerning specific information and was reliable for discriminating the dominant minerals. Due to the continuous freezing, rocking, and drying procedures necessary for the sieving, the natural form of the other sediments was altered as the clumps or shaped organic materials were disrupted or changed. This made the substrate assessment difficult to compare to the fresh samples collected in the field. Furthermore, the method is very time consuming and space requires made it difficult to process large number of samples.

Correlating acoustic classes with physical substrate types

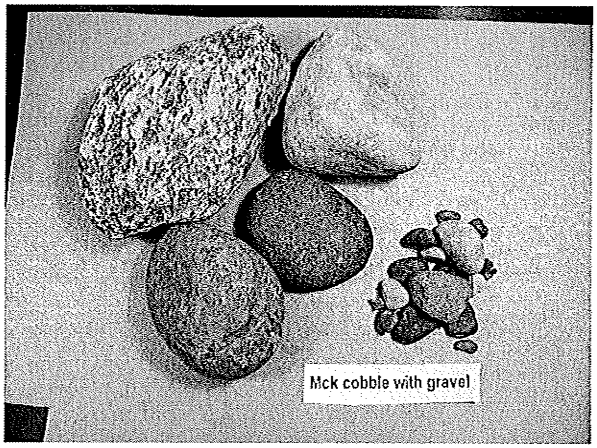
It is well known that the acoustic classes have been interpreted and characterized from the shape of the acoustic echo, but this is not a direct measurement of the grain size or the weight of all the components. At best this data contains general information regarding the hardness and the roughness which is contributed by the major sediment components. To verify the acoustic classes, the substrate samples are needed and the substrate type is simply named after the dominant components in the sediment. For example, typical sediments for the Mackenzie River were separated into twelve substrate types (Figure 10A, 10B). The Mackenzie River was selected because the substrate types were much more homogeneous in many of the survey patches.

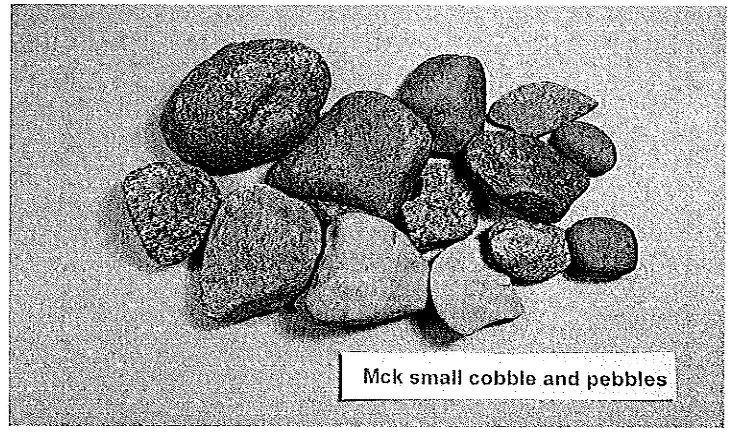
An acoustic class was expected to overlay a physical substrate type in space by ground-truth method, i.e. acoustic tracking and benthic sampling concurrent. Unfortunately, this type of correlation was probably low and most cases were more like the illustration in Figure 11. What acoustic class matched a specific benthic site labeled as a physical substrate type? Those close to each other in space were assigned one of the acoustic classes to a physical substrate type by counting the largest number of the class points near or by selecting the closest class to the benthic site. In some circumstances, a multivariate analysis was required to obtain the best fit.

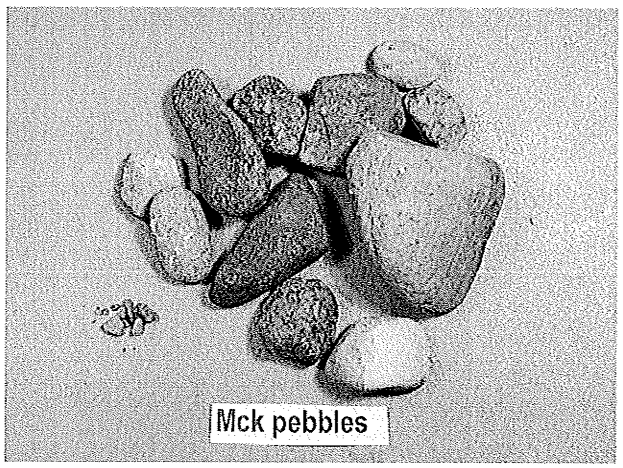
Correspondence analysis (CA) is a descriptive/exploratory technique designed to analyze a simple two-way contingency table containing some measure of correspondence between the rows and columns. It was often used to examine the relationships among individuals simultaneously, for example, the species responses at sites along a gradient.

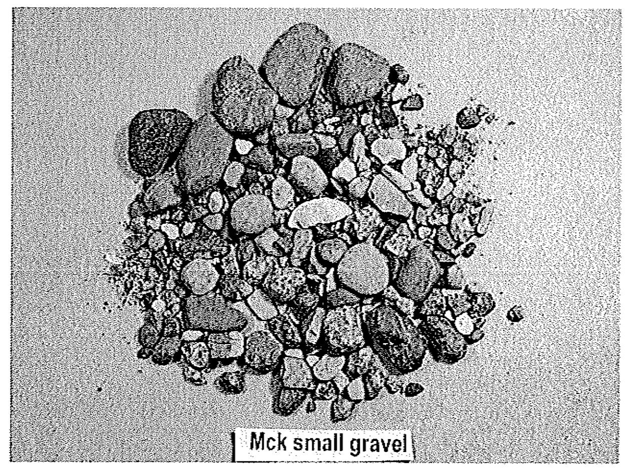
The relationship of the acoustic classes and the sampling sites was similar to this case. A good example for the application of the CA is the data collected from the Red River upstream of the Floodgates. However, the CA was not appropriate for doing a large number of samples from Numao Lake and Principal Components Analysis (PCA) was used.

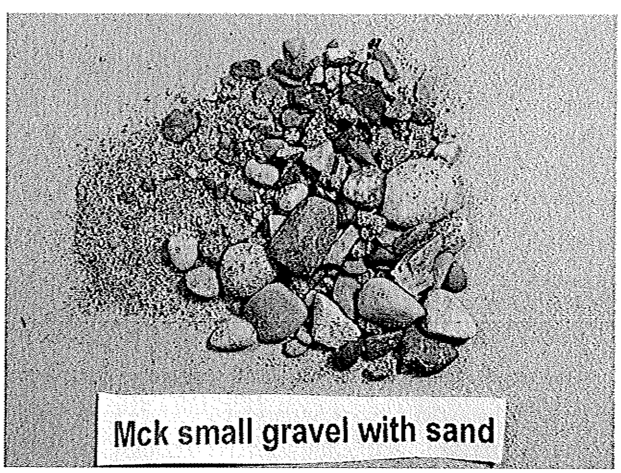
Figure10A. Sediment types from the Mackenzie River


Mck cobble with gravel


Mck small cobble and pebbles


Mck pebbles


Mck small gravel


Mck small gravel with sand

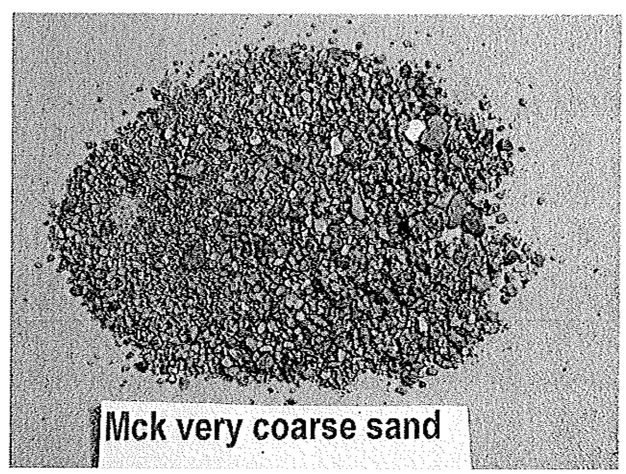
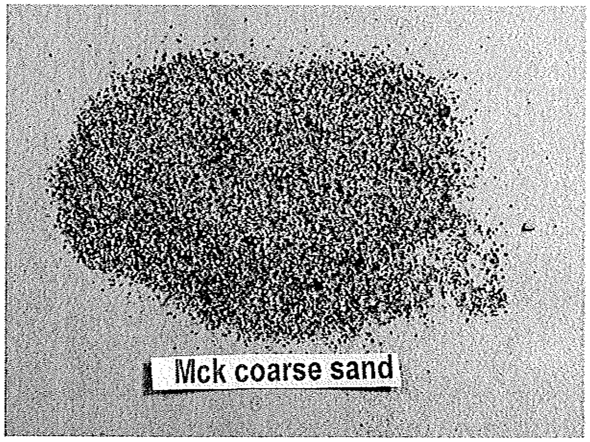
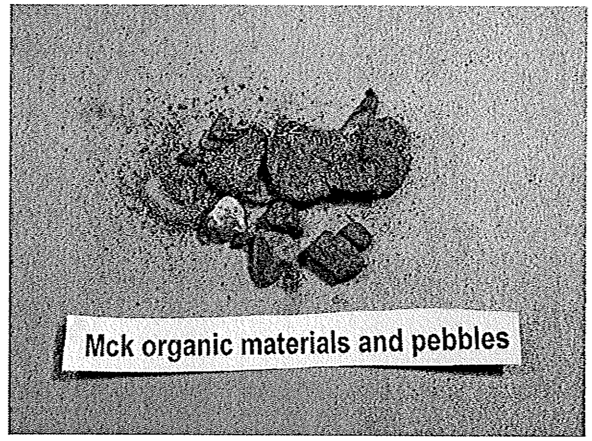
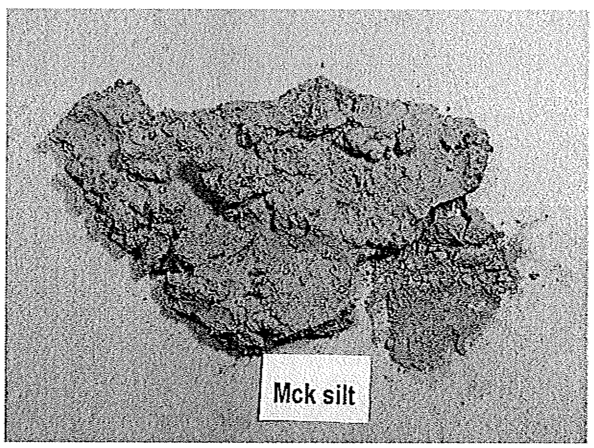
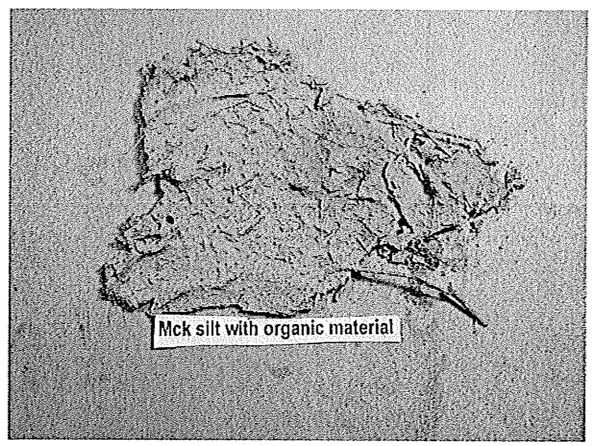

Mck very coarse sand

Figure 10B. Sediment types from the Mackenzie River Continued


Mck coarse sand


Mck organic materials and pebbles


Mck silt


Mck silt with organic material

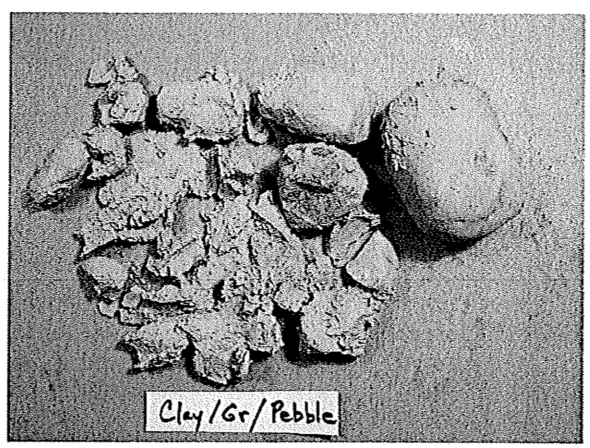
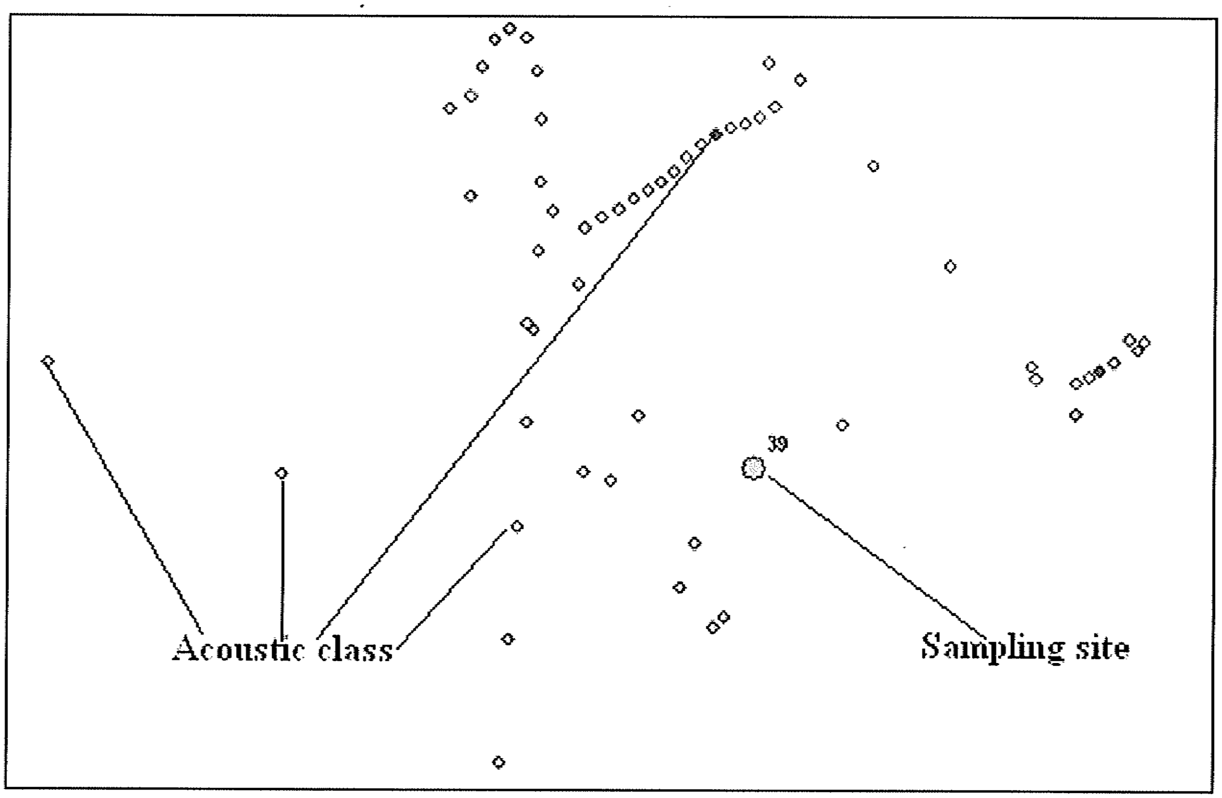

Clay/Gr/Pebble

Figure 11. Acoustic classes from one of the sampling sites in Numao Lake, the Winnipeg River (See Figure 3D, P30)


39
Acoustic class
Sampling site

Geo-processing in GIS

The QTC software series displays geo-referenced track points and color-coded acoustic classes on a window (QTC IMPACT^{TM}) (See Materials and Methods, P48) and also gives a continuous coverage for bathymetry and acoustic pattern (QTC CLAM) (See Literature Review, P13). However, there were major limitations to the QTC system since the interface with GIS was essentially nonexistent. Mapping for this thesis used GIS to create, merge and display virtually all the geo-referenced data at any desired scale. In this study, a general algorithm was designed for the bathymetry and the substrate patterns after the final classified acoustic data were imported into the ArcGIS (version 9.0) and the Arc/Info (version 7.1)

Preparing a base map

The base map is the most accurate spatial database within a data system. Base maps are comprised of land, water and other fundamental layers. Because base maps tend to serve as the reference point when creating other spatial databases, they have the highest level of accuracy. Different level (provincial, national, even continent), scale (1: 1000 to millions), and theme (land use, water systems, etc) maps should be prepared for this research. The three available maps covering the five water systems included the 1:20,000 Manitoba Map, displaying the hydrological and topographical layers, the 1:50,000 Manitoba Ortho-photos, and the 1:50,000 Canadian Natural Resources Map. These maps were often referred to as the base maps for making a boundary of the survey data.

Setting a datum and projection zone

As with a base map, selecting an appropriate datum and a projection zone was quite critical when a new layer was created for the spatial analysis. WGS 1984 be set to create XY data, but the selection of a UTM projection zone be varied with the survey locations of water systems within the North America Projection System, i.e., the Winnipeg River is in NAD_1983_UTM_Zone_14N.

Creating Comma-limited text (CSV) data

The classified acoustic data was imported into MS Excel where the QTC data format (.dat or .seabed) was saved as a CSV file with field names.

Geo-visualizing CSV data

In ArcMap, a CSV table was added for an Event with WGS_1984 (geodetic XY data published by World Geography Society in 1984). Then the data was exported in a shapefile. Note that this data format was projected with an appropriate UTM zone in the ArcMap Tools. The projected shapefile was precisely displayed within a river on the base map if the projection zone incorrectly set.

Limiting a survey area

In general, a base map is well constructed in a fixed scale or resolution. As it is difficult to show each detailed theme and to update their changes over time, a river or lake section on a base map does not always meet the specific requirements for a survey area. In other words, some parts of the visualized survey data were often beyond the boundary of the section. Under such circumstances, it was necessary to create polygon(s) to limit the survey area on the reference river or lake and to be careful to select geodetic control entities (survey areas, shoreline, islands and bridges, etc.) on the base map when the polygon(s) and were edited in order to outline closely the parts of the survey data beyond the boundary of the river or lake. This work was done using the 'Polygon Edit'. Note that the boundary polygon was projected in the same zone as the geo-referenced acoustic data.

Interpolating point data

The point data acquired from the QTC VIEW^{TM} and the sediment grabs facilitated sedimentary information regarding the bottom substrate at a particular survey area. It was helpful to understand the distribution of the bathymetry and the acoustic classes that were measured at specific locations, but it was far easier to see the spatial patterns in the data if this information was displayed as a continuous picture. It was necessary to introduce the values of the parameters at points that had not been directly sampled to create the continuous picture of the floor within this survey area.

Interpolation is based on the idea that points that are close to one another in space have more similar characteristics than points that are further away. Once the point data for the given parameters has been converted to raster data using an interpolation technique, the data can be readily compared with the other parameters. For this project, the depths and the Q values were the two key parameters to be used for interpolation.

Four alternative interpolations (TIN and Topogrid, IDW and Kriging) were all tested to determine their accuracy in the construction of bathymetric maps (RMSE or Rooted Mean Square Error was calculated on large data sets in ArcMap 9.0), substrate adaptation (how well were the color-coded acoustic classes matched to interpolated colorful acoustic patterns), image boundary effort (whether a polygon was able to be internalized for the boundary of a survey area), and visual effect (the smoothness of contour lines and likeliness of a raster image), Topogrid was finally selected to interpolate the QTC data.

Clipping to survey area shape

According to interpolation theory, the predicting points are evenly inserted in all directions around its neighboring points. A rectangular raster image was formed after interpolating on the acoustic track point data, no matter how the points were deployed. Generally the acoustic point data took the shape of the bank curves of a water body or a survey area, but the interpolating result was certain to extend the survey area. Fundamentally, the survey area that was extended by an interpolating grid image was clipped for a specific purpose by the previous boundary polygon.

Animating fish track

Unlike the QTC5, the VEMCO VR2 and the VR60 only recorded the date and time of the valid detections of transmitter codes. No GPS data were linked to the receiver automatically to mark the position of each fish. The only available means was to record the location of the VEMCO VR2 (fixed receiver) and a boat with the VR60 (mobile receiver) with a hand held GPS set. Considering the cost and the need for constant long-term data collection of fish movements, fish were tracked using the VEMCO VR2.

A specific program was designed by the Spatial Mapping Ltd. Co. and Dr. Dick, and tested by Colin Gallagher and Aihui Yang to display fish track based on the auto-positioning records from fixed receivers where the directions and the distances were calculated by a triangular algorithm. The geo-positions of the animated fish locations were inserted between VR2 receivers in a linear proportion. Since the program concentrated on displaying the fish track, the current or historical signal data were queried in real time on the map as long as there was a need to design a suitable database framework. Then the VR2 raw data was imported / parsed to the database, and eventually, simulating in the ArcGIS. Microsoft Access was used as a platform to design the database and the interface was designed for the user's data input/confirmation and was embedded into the ArcGIS (version 9.0) as a data load extension. There were a series of sequential steps to be implemented before an animation of a fish track was displayed.

Following the transfer and conversion of the fish track database into shapefiles, simple spatial analytical tools such as kernel density (calculates a magnitude per unit area from the simulation points of fish movement) and minimum convex polygon were used to explore the approximate movement pattern and habitat use.

Data organization and query

The data/sample collection and analysis required on-site field descriptions, processed data records, derived analysis tables as well as intermediate image files in order to relate directly or indirectly to the bathymetry mapping and the substrate patterns. As a result, it was necessary to organize all the data sources in order to efficiently access or query.

Acoustic attribute table

Since the acoustic data from the QTC VIEW^{TM} system was a massive point file (from hundreds to millions of records), it was not necessary to list all the records in a document. The final classification file was saved as the comma-delimit text in a spreadsheet. Each record of the QTC data in the final classification file contains the data stamp, the time, the latitude and longitude (given by the GPS), the depth (given by the echo sounder), the Q1, Q2, Q3 values, the class name, a confidence percentage and probability percentage (given by the QTC IMPACT^{TM}). Table 3 only shows a small part (36 records) of a master spreadsheet (58532 records). While the raw acoustic data was processed using the QTC IMPACT^{TM}, a directory was being created to position all of the data files in order in terms of the survey time.

Benthic record inventory

In addition to the collection of sediment samples for analysis, a number of on-site field observations such as the descriptions of the bottom probing and the visual observation, i.e. bedrock and hard clay or other sediments were completed. A variety of substrate types were described and labeled at each site after the visual classification (all

Table 3 Part of master spreadsheet of acoustic data

Microsoft Excel - floodgates1seabed

File Edit View Insert Format Tools Data Window Help

A1 = date_stamp

	A	B	C	D	E	F	G	H	I	J	K	L
1	date_stam	time_stam	longitude	latitude	depth	Q1	Q2	Q3	class_conf	probability	classID	class_name
2	20020920	1.11E+08	-1509875	5901655	-2.74	-1.23005	1.200745	1.601265	99	6	1	CLASS_01
3	20020920	1.11E+08	-1509875	5901654	-2.73	-1.39742	1.069585	1.458315	99	5	1	CLASS_01
4	20020920	1.11E+08	-1509875	5901653	-2.72	-1.05806	0.987727	1.275913	99	11	1	CLASS_01
5	20020920	1.11E+08	-1509875	5901652	-2.71	-0.91296	1.151654	1.510207	99	13	1	CLASS_01
6	20020920	1.11E+08	-1509875	5901652	-2.77	-0.62197	1.306869	1.731826	99	19	1	CLASS_01
7	20020920	1.11E+08	-1509875	5901651	-2.75	-0.94857	0.976713	1.570158	99	12	1	CLASS_01
8	20020920	1.11E+08	-1509875	5901650	-2.84	-1.36819	0.925643	1.415761	99	5	1	CLASS_01
9	20020920	1.11E+08	-1509875	5901650	-2.79	-1.18639	1.236043	1.473556	99	7	1	CLASS_01
10	20020920	1.11E+08	-1509875	5901649	-2.84	-1.09912	1.088791	1.480618	99	9	1	CLASS_01
11	20020920	1.11E+08	-1509874	5901648	-2.84	-1.38408	1.215018	1.554733	99	4	1	CLASS_01
12	20020920	1.11E+08	-1509874	5901647	-2.89	-1.43406	1.072631	1.59161	99	4	1	CLASS_01
13	20020920	1.11E+08	-1509874	5901647	-2.99	-1.61657	1.443514	1.600367	99	2	1	CLASS_01
14	20020920	1.11E+08	-1509874	5901646	-3.01	-1.35951	1.186236	1.580244	99	5	1	CLASS_01
15	20020920	1.11E+08	-1509874	5901645	-3.01	-1.42714	1.275821	1.697198	99	3	1	CLASS_01
16	20020920	1.11E+08	-1509874	5901645	-3.06	-1.5119	1.295794	1.518471	99	3	1	CLASS_01
17	20020920	1.11E+08	-1509874	5901644	-3.03	-1.64053	1.21145	1.555646	99	2	1	CLASS_01
18	20020920	1.11E+08	-1509874	5901643	-2.94	-1.58498	1.335561	1.617829	99	2	1	CLASS_01
19	20020920	1.11E+08	-1509874	5901642	-3.01	-1.6303	1.27965	1.577937	99	2	1	CLASS_01
20	20020920	1.11E+08	-1509874	5901642	-3.01	-1.73909	1.201618	1.673656	99	1	1	CLASS_01
21	20020920	1.11E+08	-1509874	5901641	-3.03	-1.51589	1.047297	1.569793	99	3	1	CLASS_01
22	20020920	1.11E+08	-1509874	5901640	-3.06	-1.55741	1.318473	1.586079	99	3	1	CLASS_01
23	20020920	1.11E+08	-1509874	5901640	-2.99	-1.28795	1.159165	1.527901	99	6	1	CLASS_01
24	20020920	1.11E+08	-1509874	5901639	-2.99	-1.20372	1.26745	1.688506	99	6	1	CLASS_01
25	20020920	1.11E+08	-1509874	5901638	-3.06	-1.50237	1.275447	1.556247	99	3	1	CLASS_01
26	20020920	1.11E+08	-1509874	5901638	-3.06	-1.63078	1.132255	1.596558	99	2	1	CLASS_01
27	20020920	1.11E+08	-1509874	5901637	-3.12	-1.52716	1.145137	1.580282	99	3	1	CLASS_01
28	20020920	1.11E+08	-1509874	5901636	-3.07	-1.59073	1.343866	1.638498	99	2	1	CLASS_01
29	20020920	1.11E+08	-1509874	5901635	-3.01	-1.71053	1.179184	1.571686	99	2	1	CLASS_01
30	20020920	1.11E+08	-1509874	5901635	-2.99	-1.80057	1.425079	1.636554	99	1	1	CLASS_01
31	20020920	1.11E+08	-1509874	5901634	-3.01	-1.88319	1.262084	1.637217	99	1	1	CLASS_01
32	20020920	1.11E+08	-1509874	5901633	-2.99	-1.62769	1.461431	1.689904	99	2	1	CLASS_01
33	20020920	1.11E+08	-1509873	5901632	-3.06	-1.66944	1.337917	1.685108	99	2	1	CLASS_01
34	20020920	1.11E+08	-1509873	5901632	-3.08	-1.35887	1.32777	1.737627	99	4	1	CLASS_01
35	20020920	1.11E+08	-1509873	5901631	-3.07	-1.4892	1.338843	1.657917	99	3	1	CLASS_01

floodgates1seabed

Ready NUM

survey sites) and the sieving classification (just at the Red River upstream of the Floodgates site and at the Numao Lake in the Winnipeg River). The final inventories were designed as the following tables: the Red River upstream of the Floodgates (Table 4), Numao Lake, the Winnipeg River (Table 5), Seven Sisters, the Winnipeg River (Table 6), Horseshoe Bend to Great River Bear, the Mackenzie River (Table 7), Chitty Lake (Table 8) and Wormy Lake (Table 9)

Telemetric data form

In order to run fish track program successfully in GIS, four kinds of data (fish ID, tag ID, Receiver ID and Transmitted fix data were downloaded from the VR2 receiver) and organized to support the database design. The following file (Table 10) was used to access/confirm the data.

GIS file directory

Developing the GIS files required the generation of the initial, intermediate, and final data or images for processing, otherwise querying the data or transferring a file would become time-consuming and inefficient and perhaps impossible if they were not organized. Consequently, the folders along the path were made up of the CSV-Excel, Export-Shapefile, Shapefile, TIN, Topogrid, Kriging, IDW, Contours, Polygon, etc. It was not necessary to display all of the intermediate data, but rather to know how to generate the final map from them. The final maps are as follows:

1. *Basic thematic layers*
   - Geo-referenced an acoustic point file
   - Categorical interpolation files
   - Bathymetric files
   - Fish animation track files
2. *Layer draping*
   - Intersecting for correlation between the themes
   - Clipping for the extraction of a theme
   - Merging for the synthetic characteristics among the themes

Supporting Data

There were two other sources of the QTC data and benthic samples quoted for the comparison of the Q1 values in this thesis. They came from Falcon Lake and Stephenfield Reservoir near Winnipeg, Manitoba. In addition, the water flow data from Seven Sisters, Winnipeg River was provided by Manitoba Hydro to evaluate the effects on the movement of lake sturgeons.

Table 4 Benthic records and descriptions of The Red River upstream of the Floodgates

Grab_number	Longitude_decdeg	Latitude_decdeg	Substrates	Description	Sample_id	Location	Date_dmy
1	-97.129072	49.737593	pebble/slity clay	90/10	A	Floodgates	16/15/2003
2	-97.127951	49.737142	silty clay	15/85	B	Floodgates	16/15/2003
3	-97.129202	49.736751	gravel/silty clay	10/90	C	Floodgates	16/15/2003
4	-97.127608	49.734693	silty clay	15/80	D	Floodgates	16/15/2003
5	-97.127189	49.735329	gravel/silty clay	30/60	E	Floodgates	16/15/2003
6	-97.126454	49.735371	silty clay	10/90	F	Floodgates	16/15/2003
7	-97.129005	49.739674	pebble/silty clay	80/20	G	Floodgates	16/15/2003
8	-97.128409	49.739736	organic silty clay	mixed organic materieal	H	Floodgates	16/15/2003
9	-97.128159	49.739536	organic silty clay	mixed organic materieal	I	Floodgates	16/15/2003
10	-97.127518	49.739378	organic silty clay	mixed organic materieal	J	Floodgates	16/15/2003

Table 5 Benthic records and descriptions of Numao Lake, the Winnipeg River

Grab_number	Longitude_decdeg	Latitude_decdeg	Substrates	Description	Depth_m	Location	Date_dmy
1	-95.617915	50.18176167	pebble/gravel/sand	30/50/20		Numao Lake	7/10/2003
2	-95.617455	50.17976667	sand/silt	90/10 a little	10	Numao Lake	7/10/2003
3	-95.61731333	50.17800167	sand/silt	90/10 a little	13	Numao Lake	7/10/2003
4	-95.61707333	50.17587333	sand/silt	90/10 full of grab	18	Numao Lake	7/10/2003
5	-95.61704167	50.17316333	sand/gravel	90/10 a little	17	Numao Lake	7/10/2003
6	-95.61674	50.171415		empty	10.7	Numao Lake	7/10/2003
7	-95.616835	50.17134333	sand/silt/organic	70/25/5		Numao Lake	7/10/2003
8	-95.61713333	50.17038333		empty	2	Numao Lake	7/10/2003
9	-95.61528833	50.171385		empty	6	Numao Lake	7/10/2003
10	-95.61468333	50.17133333	sand/silt/organic	60/30/10	2.5	Numao Lake	7/10/2003
11	-95.61570667	50.17053167	.	empty	6	Numao Lake	7/10/2003
12	-95.61589667	50.17021333	sand/silt/organic	60/30/10		Numao Lake	7/10/2003
13	-95.625455	50.173655		empty	13.9	Numao Lake	7/10/2003
14	-95.62588	50.170405	sand/silt/organic	70/10/20	2.8	Numao Lake	7/10/2003
15	-95.62705667	50.17116833		rock	7.8	Numao Lake	7/10/2003
16	-95.62750167	50.17329		empty	24	Numao Lake	7/10/2003
17	-95.62805667	50.17600833	sand/organic/mussel	80/10/10	12.6	Numao Lake	7/10/2003
18	-95.62837667	50.17750167	sand/gravel	90/10	8.9	Numao Lake	7/10/2003
19	-95.6282	50.17918667	sand/gravel	70/30	12	Numao Lake	7/10/2003
20	-95.62848667	50.180435		rock	6	Numao Lake	7/10/2003
21	-95.62894667	50.181055		empty	6	Numao Lake	7/10/2003
22	-95.62917	50.18149167		hard clay	4.5	Numao Lake	7/10/2003
23	-95.62939167	50.18183333	sand	100/0	3.8	Numao Lake	7/10/2003
24	-95.62929667	50.18196833	sand/gravel/organic			Numao Lake	7/10/2003
25	-95.62487833	50.17988667	sand/silt/gravel	80/10/10	24	Numao Lake	7/10/2003
26	-95.61276667	50.17560167	fine sand/silt/organic	70/20/10	15	Numao Lake	7/10/2003
27	-95.612035	50.17922667	sand/silt/mussel/organic	60/20/10/10	12	Numao Lake	7/10/2003
28	-95.61133667	50.18173833	sand/silt/organic	50/30/20	2	Numao Lake	7/10/2003
29	-95.609715	50.18049833		empty	1.8	Numao Lake	7/10/2003
30	-95.60919	50.18016333		empty	1.9	Numao Lake	7/10/2003
31	-95.60879333	50.178615		empty	1.5	Numao Lake	7/10/2003
32	-95.60927	50.17658		empty	10	Numao Lake	7/10/2003
33	-95.60974667	50.175205	sand/gravel	70/30	8.3	Numao Lake	7/10/2003
34	-95.61049333	50.173505	sand/silt/organic	50/40/10	5.5	Numao Lake	7/10/2003
35	-95.61082833	50.17220167	sand/silt/organic	50/30/20	1.7	Numao Lake	7/10/2003
36	-95.61221	50.17278167	sand/gravel	70/30	5.6	Numao Lake	7/10/2003
37	-95.61375167	50.173735	pebble/gravel/sand	60/30/10	14	Numao Lake	7/10/2003
38	-95.61419667	50.17397333		empty	16.3	Numao Lake	7/10/2003
39	-95.61515	50.17479167	sand	100/0	18.3	Numao Lake	7/10/2003

Table 6 Benthic records and descriptions of Seven Sisters, the Winnipeg River

Grab_number	Description	Lat	Long	Latitude_decdeg	Longitude_decdeg	Location	Date
1	Pebbles	50.07796648	96.01813476	50.12994413	-96.0302246	Seven Sisters	7/9/2005
2	Gravels/sand	50.07796795	96.01813395	50.12994658	-96.03022325	Seven Sisters	7/9/2005
3	Sand			50.12679667	-96.035815	Seven Sisters	7/9/2005
4	Sand			50.12970333	-96.03717833	Seven Sisters	7/9/2005
1	Nothing in grab, hard pan or rock?	50.081851	96.027858	50.13641833	-96.04643	Seven Sisters	6/5/2005
2	Nothing in grab, hard pan or rock?	50.083086	96.024653	50.13847667	-96.04108833	Seven Sisters	6/5/2005
3	Wood/ leaves/ silt/ trace of clay	50.080276	96.025177	50.13379333	-96.04196167	Seven Sisters	6/5/2005
4	Nothing in grab, hard pan or rock?	50.080709	96.024253	50.134515	-96.04042167	Seven Sisters	6/5/2005
5	Nothing in grab, hard pan or rock?	50.081354	96.023408	50.13559	-96.03901333	Seven Sisters	6/5/2005
6	Nothing in grab, hard pan or rock?	50.08207	96.0222	50.13678333	-96.037	Seven Sisters	6/5/2005
7	Nothing in grab, hard pan or rock?	50.079606	96.024411	50.13267667	-96.040685	Seven Sisters	6/5/2005
8	Nothing in grab, hard pan or rock?	50.079758	96.023117	50.13293	-96.03852833	Seven Sisters	6/5/2005
9	Nothing in grab, hard pan or rock?	50.080527	96.021745	50.13421167	-96.03624167	Seven Sisters	6/5/2005
10	Nothing in grab, hard pan or rock?	50.081197	96.020218	50.13532833	-96.03369667	Seven Sisters	6/5/2005
11	Nothing in grab, hard pan or rock?	50.079636	96.018995	50.13272667	-96.03165833	Seven Sisters	6/5/2005
12	Nothing in grab, hard pan or rock?	50.079104	96.021047	50.13184	-96.03507833	Seven Sisters	6/5/2005
13	Sand, very small amount	50.078126	96.022628	50.13021	-96.03771333	Seven Sisters	6/5/2005
14	Fine sand, very small amount	50.077849	96.023277	50.12974833	-96.038795	Seven Sisters	6/5/2005
15	Nothing in grab, hard pan or rock?	50.077475	96.021386	50.129125	-96.03564333	Seven Sisters	6/5/2005
16	Nothing in grab, hard pan or rock?	50.076353	96.019377	50.127255	-96.032295	Seven Sisters	6/5/2005
17	Pebbles and trace of sand	50.076955	96.016832	50.12825833	-96.02805333	Seven Sisters	6/5/2005
18	Silt/ organic/ fine clay/ traces of sand	50.078051	96.017079	50.130085	-96.028465	Seven Sisters	6/5/2005
19	Nothing in grab, hard pan or rock?	50.077817	96.017138	50.129695	-96.02856333	Seven Sisters	6/5/2005
20	Nothing in grab, hard pan or rock?	50.076052	96.020587	50.12675333	-96.03431167	Seven Sisters	6/5/2005
21	Nothing in grab, hard pan or rock?	50.07537	96.021213	50.12561667	-96.035355	Seven Sisters	6/5/2005
22	Fine sand, very small amount	50.073627	96.020741	50.12271167	-96.03456833	Seven Sisters	6/5/2005
23	Nothing in grab, hard pan or rock?	50.124245	96.039473	50.207075	-96.06578833	Seven Sisters	6/5/2005

Table 7 Benthic records and descriptions of Horseshoe Bend to Great Bear River, the Mackenzie River

Grab_number	Longi	Lat	Longitude_decdeg	Latitude_decdeg	Substrates	Description	Depth_m	Location	Date_d
4	24.145	14.726	-134.4024167	68.24543333	fine sand	100/0		Horseshoe	6/8/2
5	23.119	54.616	-134.3853167	67.91026667	fine sand	100/0		MK03	6/8/2
6	8.238	47.653	-134.1373	67.79421667	fine sand/silt	90/10		Rengleng	7/8/2
7	7.6	47.824	-134.1266667	67.79706667	fine/coarse sand/gravel/pebble	60/20/10/10		Rengleng	7/8/2
8	36.058	40.964	-134.6009667	67.68273333	fine sand/silt	90/10		Peele	7/8/2
9	35.7023	40.88	-134.5950383	67.68133333	fine sand/silt	70/30		Peele	7/8/2
10	36.1493	40.8995	-134.6024883	67.68165833	silt/clay/fine sand	10/80/10		Peele	7/8/2
11	46.707	25.927	-133.77845	67.43211667	fine sand/silt	70/30		Arctic RR	8/8/2
12	17.888	18.756	-132.2981333	67.3126	fine sand			MK10	8/8/2
13	29.6408	27.9729	-131.4024167	67.24543333	silt/clay	90/10		Travaillant	9/8/2
14	29.814	27.485	-131.3853167	67.91026667	silt/clay/sand	20/80		Travaillant	10/8/2
15	1.5289	45.236	-131.1373	67.79421667	silt/clay/sand	10/80/10		Ontaratue	10/8/2
16	57.227	27.748	-131.1266667	67.79706667	organic materials/sand	80/20		Loon	11/8/2
17	58.3204	28.1876	-131.6009667	67.68273333	hard silt/sand	90/10		Loon	11/8/2
18	34.6371	17.5737	-131.5950383	67.68133333	gravel/coarse/fine sand/organ	50/15/5/30		Hare	11/8/2
19	50.564	47.877	-131.6024883	67.68165833	coarse/fine sand/silt/organ	10/80/10		MK17	12/8/2
20	48.51	47.836	-131.77845	67.43211667	hard silt/clay	30/70		MK17	12/8/2
21	49.463	47.353	-131.2981333	67.3126	rock	20/10/70		MK17	12/8/2
22	46.98	39.9627	-131.4940133	67.466215	fine sand	100/0		MK19	12/8/2
23	50.6803	41.0261	-131.4969	67.45808333	fine sand	100/0		Mountain	13/8/20
24	4.662	17.843	-131.0254817	67.75393333	cobble/pebble	90/10		MK22	13/8/20
25	4.9979	17.5833	-131.9537833	67.46246667	coarse/fine sand	70/30		MK22	13/8/20
26	3.5593	17.395	-131.9720067	67.46979333	fine sand	100/0		MK22	13/8/20
27	35.955	52.517	-125.59925	64.87528333	muddy sand	60/40		Great Bear	8/15/2
28	35.821	54.061	-125.5970167	64.90101667	rock	100/0		Great Bear	8/15/2
29	34.782	54.948	-125.5797	64.9158	rock	100/0		Great Bear	8/15/2
30	36.478	53.1745	-125.6079667	64.88624167	fine sand	100/0		Great Bear	8/18/2
31	36.1171	52.3572	-125.6019517	64.87262	coarse/fine sand/silt	10/80/10		Great Bear	8/18/2

Table 8 Benthic records and descriptions of Chitty Lake

Grab_no.	Latitude_decdeg	Longitude_decdeg	Substrate	Location	Date
1	62.71081667	-114.1274917	Loonshit/organic	Chitty Lake	18/09/2004
2	62.712025	-114.1257433	Loonshit/organic	Chitty Lake	18/09/2004
3	62.713075	-114.13375	Loonshit/organic	Chitty Lake	18/09/2004
4	62.71394833	-114.1365117	Nothing in grab but visually it is boulders and organic	Chitty Lake	18/09/2004
5	62.71968	-114.1232783	Sand with small pebbles	Chitty Lake	18/09/2004
6	62.71994	-114.1236367	Organic fine sand	Chitty Lake	18/09/2004
7	62.72198333	-114.1235817	Nothing	Chitty Lake	18/09/2004
8	62.72192667	-114.1241533	Pebbles and gravel	Chitty Lake	18/09/2004
9	62.72332667	-114.1230333	Nothing but small clumps of organic	Chitty Lake	18/09/2004
10	62.723405	-114.1225633	Loonshit/organic	Chitty Lake	18/09/2004
11	62.72481167	-114.119265	Small gravel and coarse sand	Chitty Lake	18/09/2004
12	62.72633833	-114.1195833	Loonshit/organic	Chitty Lake	18/09/2004
13	62.72772833	-114.1224217	Loonshit/organic	Chitty Lake	18/09/2004
14	62.72837333	-114.12926	Nothing	Chitty Lake	18/09/2004
15	62.72831667	-114.1297167	Loonshit/organic	Chitty Lake	18/09/2004
16	62.728285	-114.1297167	Loonshit/organic	Chitty Lake	18/09/2004
17	62.72991667	-114.13595	Silt	Chitty Lake	18/09/2004
18	62.72611667	-114.1356667	Fine gravel, pebbles and coarse sand	Chitty Lake	18/09/2004
19	62.72438833	-114.1371167	Silt	Chitty Lake	18/09/2004

Table 9 Benthic records and descriptions of Wormy Lake

Grab_number	Longitude_decdeg	Latitude_decdeg	Substrates	Description	Depth_m	Location	Date_dmy
1	-68.37667522	63.68467983	Clumped organics	100 samll leaf-like loonshit	14	Wormy Lake	13/07/2004
2	-68.37518544	63.68577656	Clumped organics	100 fine particle looshit	10	Wormy Lake	13/07/2004
3	-68.37367264	63.68524211	clumped organics/sand	90/10 gritty particle loonshit	24	Wormy Lake	13/07/2004
4	-68.37919444	63.68413889	gravel/rock	small gravels / rock	2.6	Wormy Lake	14/07/2004
5	-68.37788889	63.68411111	vegetation/clumped organics	50/50 fresh vegetation and black organics	4	Wormy Lake	14/07/2004
6	-68.38338889	63.68938889	boulder	and rock	2.5	Wormy Lake	15/07/2004
7	-68.38113889	63.68972222	Clumped organics	100 brown	6	Wormy Lake	15/07/2004
8	-68.37861111	63.69	rock		2.5	Wormy Lake	15/07/2004
9	-68.37766667	63.68880556	Clumped organics	100 brown	5	Wormy Lake	15/07/2004
10	-68.37530556	63.68888889	boulder	3' to 6'		Wormy Lake	15/07/2004
11	-68.37436111	63.68727778	Clumped organics	100 brown /black underneath	8	Wormy Lake	15/07/2004
12	-68.37652778	63.68755556	clumped organics/gravel/sand	60/20/20	2.5	Wormy Lake	15/07/2004
13	-68.37808333	63.68761111	pebble/gravel/sand/silt	40/20/30/10	2.5	Wormy Lake	15/07/2004
14	-68.38025	63.68547222	clumped organics/gravel/sand	50/30/20 with boulder	2	Wormy Lake	15/07/2004
15	-68.37675	63.68538889	Clumped organics	drawed and no benthic sample	16	Wormy Lake	15/07/2004
16	-68.37677778	63.68536111		no benthic sample	15	Wormy Lake	15/07/2004
17	-68.37388889	63.68508333	Clumped organics	brown	5	Wormy Lake	15/07/2004
18	-68.37372222	63.68386111	pebble/gravel/sand	50/30/20 with boulder	2.5	Wormy Lake	15/07/2004
19	-68.37566667	63.68375	sand/solid organics	80/20	3	Wormy Lake	15/07/2004
20	-68.37713889	63.68372222	clumped organics/sand.gravel	40/40/20 with 3' boulder	2.5	Wormy Lake	15/07/2004
21	-68.37905556	63.68375	sand	100 small amount	2.5	Wormy Lake	15/07/2004
22	-68.37613889	63.68275	gravel/sand	70/30 rock with brown organics	1.5	Wormy Lake	15/07/2004
23	-68.37586111	63.68355556	pebble	large	3	Wormy Lake	15/07/2004
24	-68.37613889	63.6845		no benthic sample	12.5	Wormy Lake	15/07/2004
25	-68.37525	63.68486111	clumped organics/vegetation	95/5	12.5	Wormy Lake	15/07/2004
26	-68.37597222	63.68513889	Clumped organics	100 black and brown	14	Wormy Lake	15/07/2004
27	-68.38275	63.69272222	sand/gravel	70/30	2	Wormy Lake	15/07/2004

Table 10 Identification of Arctic char, tag and VR2 receivers in Wormy Lake

Fish no.	Date	Species	Acoustic tag ID	Weight (g)	Fork length (mm)	Release latitude (DMS)	Release longitude (DMS)	Note
1	13/7/2004	Arctic char	407	400	not recorded			
2	13/7/2004	Arctic char	90	1850	555	63°41'13.2"	68°22'56.5"	
3	14/7/2004	Arctic char	406	95	210	63°41'13.2"	68°22'56.5"	
4	14/7/2004	Arctic char	91	2200	625	63°41'13.2"	68°22'56.5"	
5	14/7/2004	Arctic char	94	1450	530	63°41'13.2"	68°22'56.5"	
6	15/7/2004	Arctic char	405	100	243	63°41'13.2"	68°22'56.5"	
7	15/7/2004	Arctic char	404	100	230	63°41'13.2"	68°22'56.5"	
8	15/7/2004	Arctic char	403	725	420	63°41'13.2"	68°22'56.5"	
9	15/7/2004	Arctic char	402	525	395	63°41'13.2"	68°22'56.5"	
10	15/7/2004	Arctic char	401	250	330	63°41'13.2"	68°22'56.5"	
11	15/7/2004	Arctic char	93	950	455	63°41'13.2"	68°22'56.5"	
12	15/7/2004	Arctic char	400	700	409	63°41'13.2"	68°22'56.5"	
13	15/7/2004	Arctic char	413	110	224	63°41'13.2"	68°22'56.5"	

CHAPTER 4 RESULTS

A total of 56 sites were assessed acoustically and 168 benthic samples were collected. They were processed for acoustic classification and verification. Telemetry has been performed on lake sturgeon, lake trout and Arctic char since 2004. The movement patterns of six fish (three lake sturgeons, two lake trout and an Arctic char) were simulated with the aid of a special program designed to process the data from the VR2 receivers. All of the geo-referenced data were integrated into maps for fish habitats in GIS.

Final bathymetric maps

Final bathymetric maps are overlapped by a raster image interpolated by using Topogrid and the contour lines derived from this raster image. The bathymetric map of the entire Red River (within Manitoba) indicates that the river is not very deep (the maximum was 15 meters) and most of the riverbed is in the shape of a slow downward slope of cross section (from shallow inshore to deep centre). A detailed map of bathymetry of the Red River upstream of the Floodgates (Figure 12) is a typical a prairie river with a main channel and moderate flows.

The bathymetric map of Numao Lake and Seven Sisters, the Winnipeg River and two sections of the Winnipeg River are displayed at an appropriate scale and intervals. The current directions are complicated by the influence of natural barriers such as islands and/or big rocks, or the anthropologic impacts of hydroelectric facilities. Thus, the topographic isolines vary greatly (Figure 13 and Figure 14), especially in Numao Lake. A deep channel is formed along the major currents displayed on the left top of the bathymetric map (Figure 13). The deepest area reaches 42 meters.

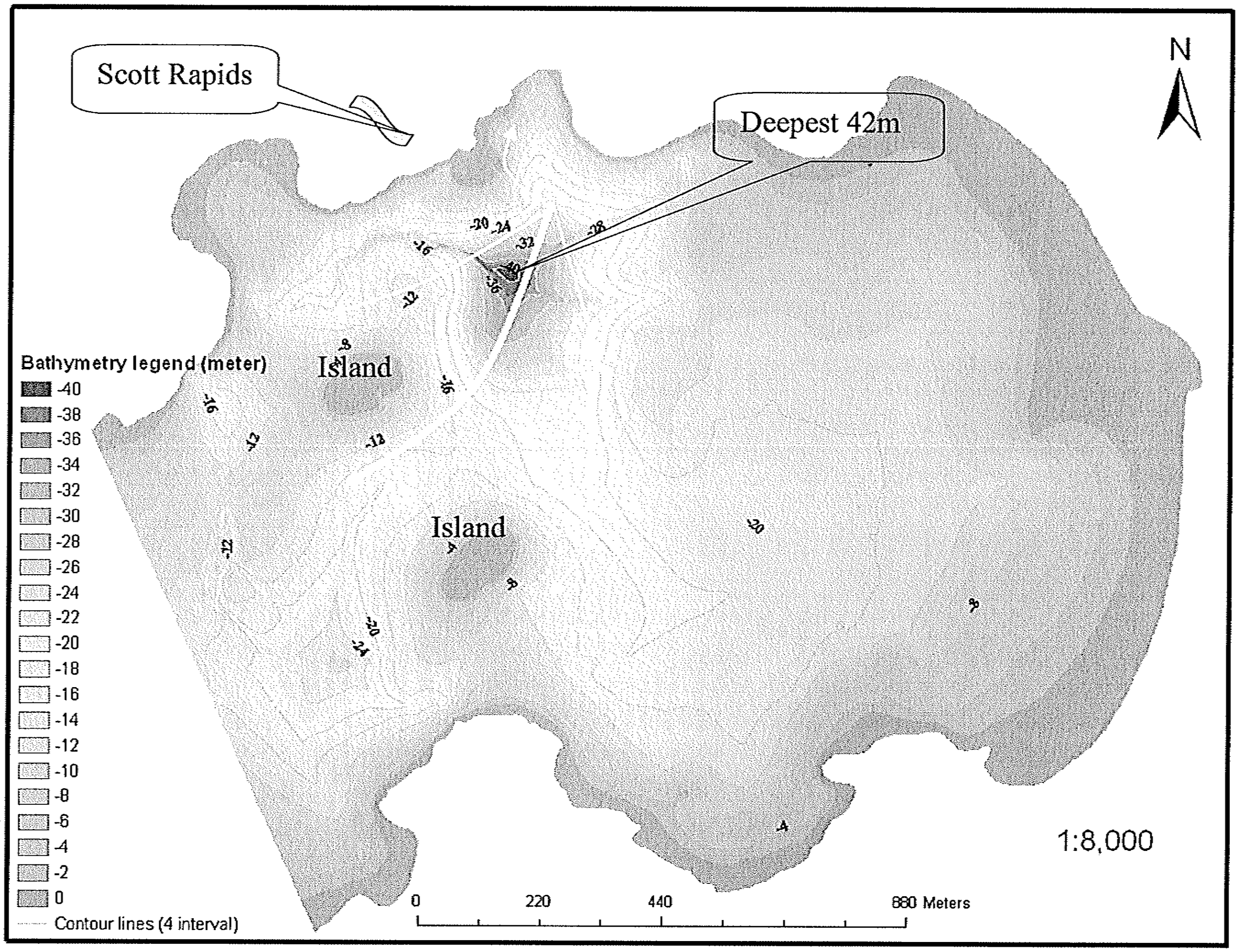
The Mackenzie River is too long to create a full bathymetry map in a window. The size and position of each area where the acoustic tracking was done is displayed separately (Figure 4). Under these circumstances, benthic sampling was required for verification along each tracking area. Hence, the bathymetric map only represented the tracking area that is discussed in detail in this thesis (Figure 15). It is impossible to display all of the bathymetric maps for the survey areas of the Mackenzie River on a regular paper size, but they can be queried in an appropriate scale such as the Horseshoe Bend (Figure 15). The Mackenzie River has on average a depth of about 13 m. The exception is Horseshoe Bend with a maximum depth of 53 m.

The two small northern lakes, Chitty Lake and Wormy Lake, have average depth of 6.7 m and 4.4 m respectively. Two deep zones occur in the south and north basin of both lakes. The maximum depth (26 m) of Chitty Lake is located at the north basin and the maximum depth (19 m) of Wormy Lake is located in the south basin (Figure 16 and Figure 17).

Figure 12. Bathymetry of the Red River upstream of the Floodgates
This figure indicates the range of the Red River upstream of the Floodgates where detailed bathymetric data was collected for this map. The location of the Red River upstream of the Floodgates can also be referred to in Figure 2, P27


N
Bathymetry legend (meter)
<VALUE>
-5
-4
-3
-2
-1
0
Contour lines (1 interval)
1:3,000
0
65
130
260 Meters

Figure 13. Bathymetry of Numao Lake, the Winnipeg River
Numao Lake is located at the middle of the Winnipeg River in Manitoba (Refer to Figure 3E, P30). This portion of the river consists of three deep channels and an extensive shallow area



Scott Rapids
Deepest 42m
N
Island
Island
Bathymetry legend (meter)
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
Contour lines (4 interval)
0
220
440
880 Meters
1:8,000

Figure 14. Bathymetry of the Seven Sister area of the Winnipeg River
Seven Sisters is downstream of Numao Lake (Refer to Figure 3D, P30). A dam was built for hydroelectric development and the river flow was markedly altered with generally low flows over the original stream bed. Water flow is regulated by turbines and a spillway, and is also affected by the Whitemouth River. Arrows indicate water flows.

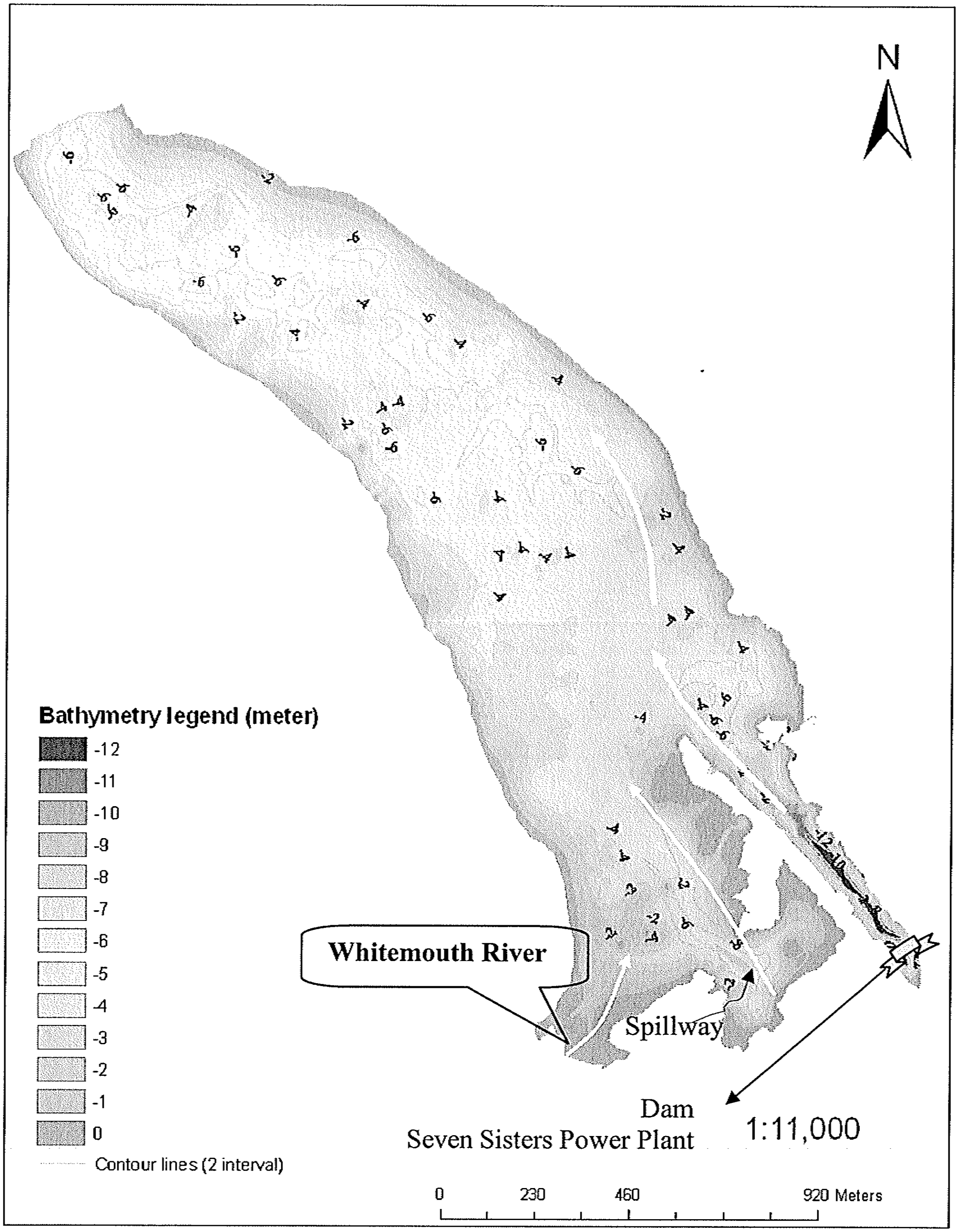

N
Bathymetry legend (meter)
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Contour lines (2 interval)
Whitemouth River
Spillway
Dam
Seven Sisters Power Plant
1:11,000
0
230
460
920 Meters

Figure 15. Bathymetry of Horseshoe Bend, the Mackenzie River
This is in the delta area of the Mackenzie River downstream. A deep "hole" is at the sharp bend of the northern Horseshoe Bend (See Figure 4C P32) for the location on the Mackenzie River.

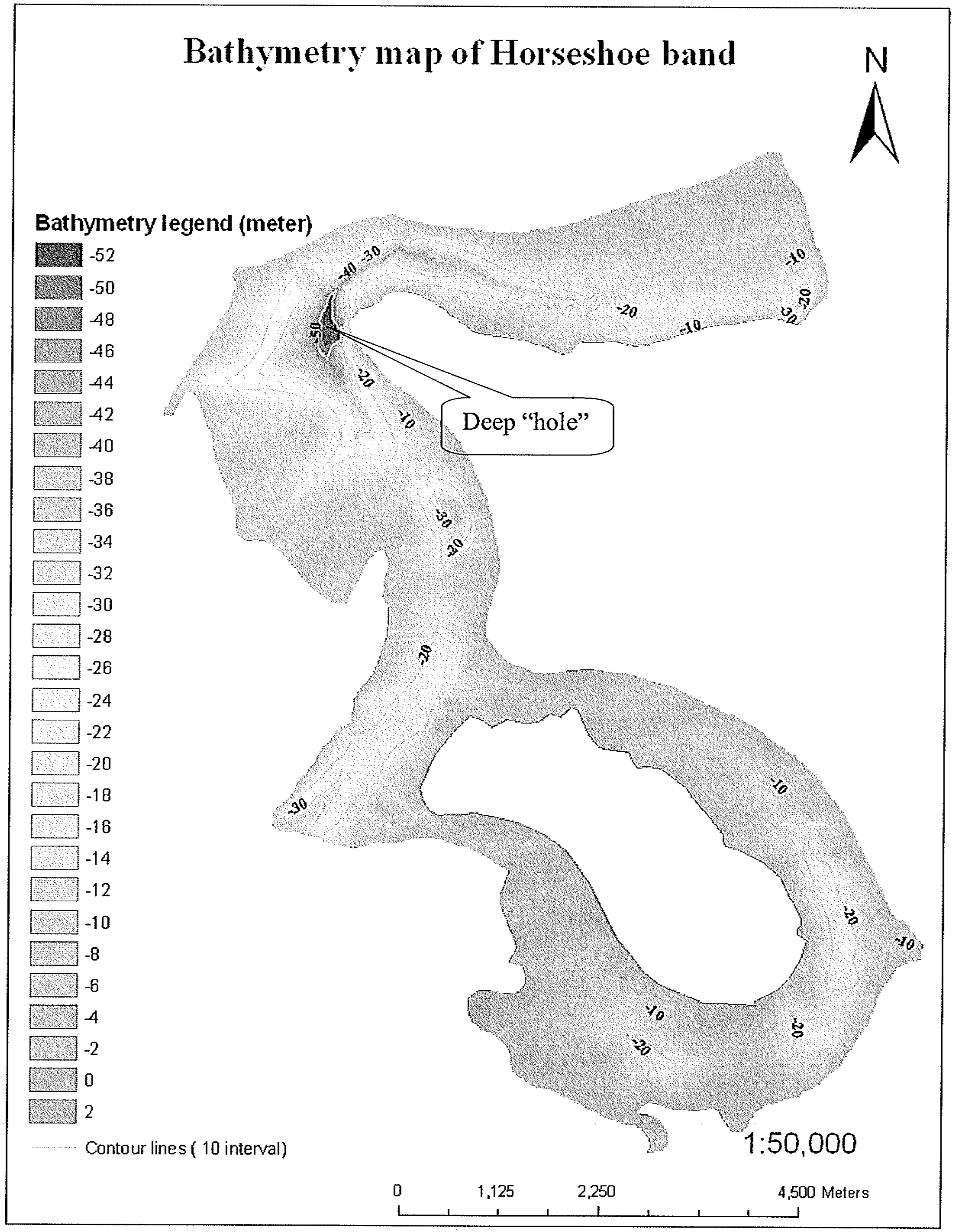

Bathymetry map of Horseshoe band
N
Bathymetry legend (meter)
-52
-50
-48
-46
-44
-42
-40
-38
-36
-34
-32
-30
-28
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
Contour lines (10 interval)
Deep "hole"
1:50,000
0
1,125
2,250
4,500 Meters

Figure 16. Bathymetry of Chitty Lake
There are two deeper basins with the deepest part of the lake in the north basin.

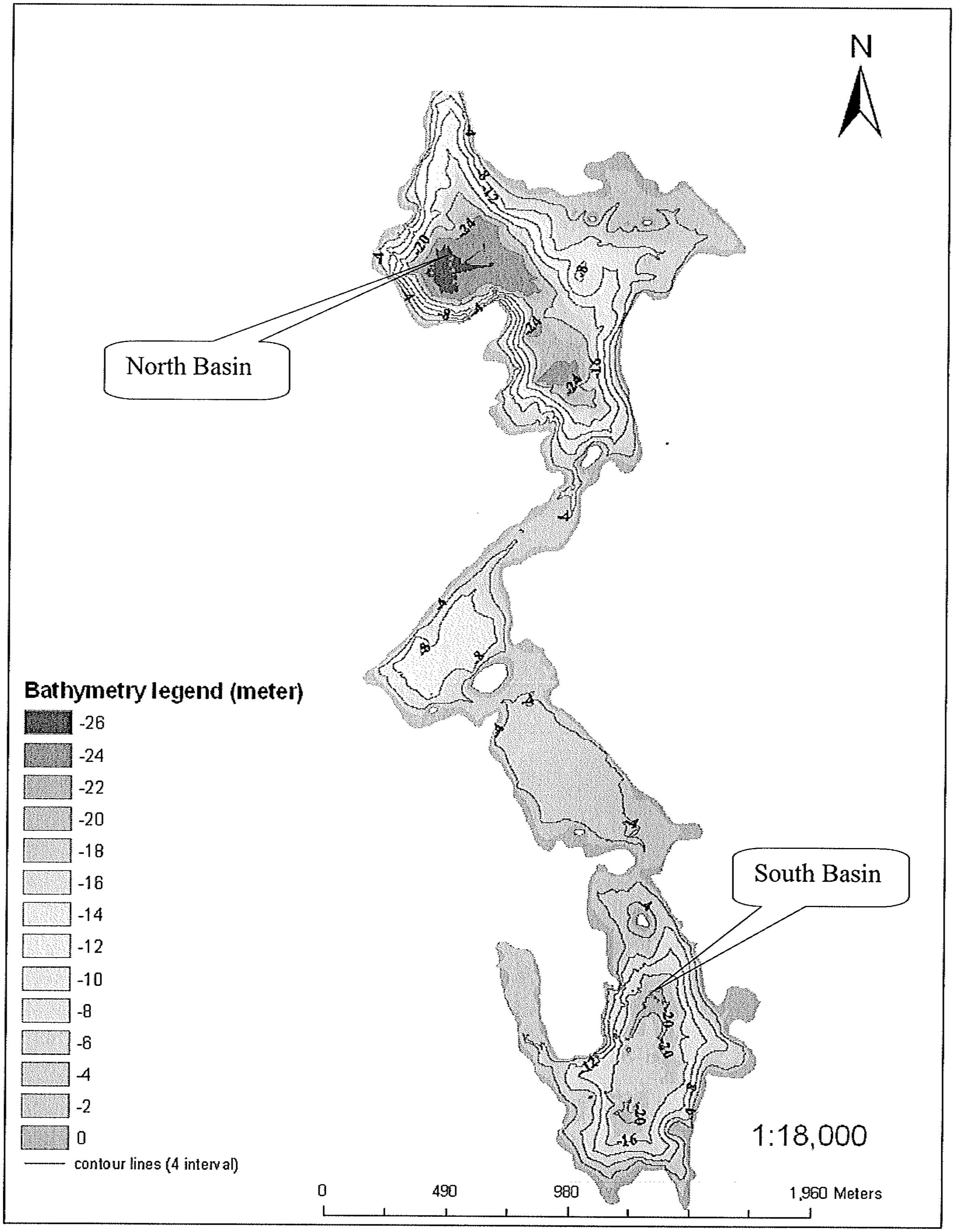
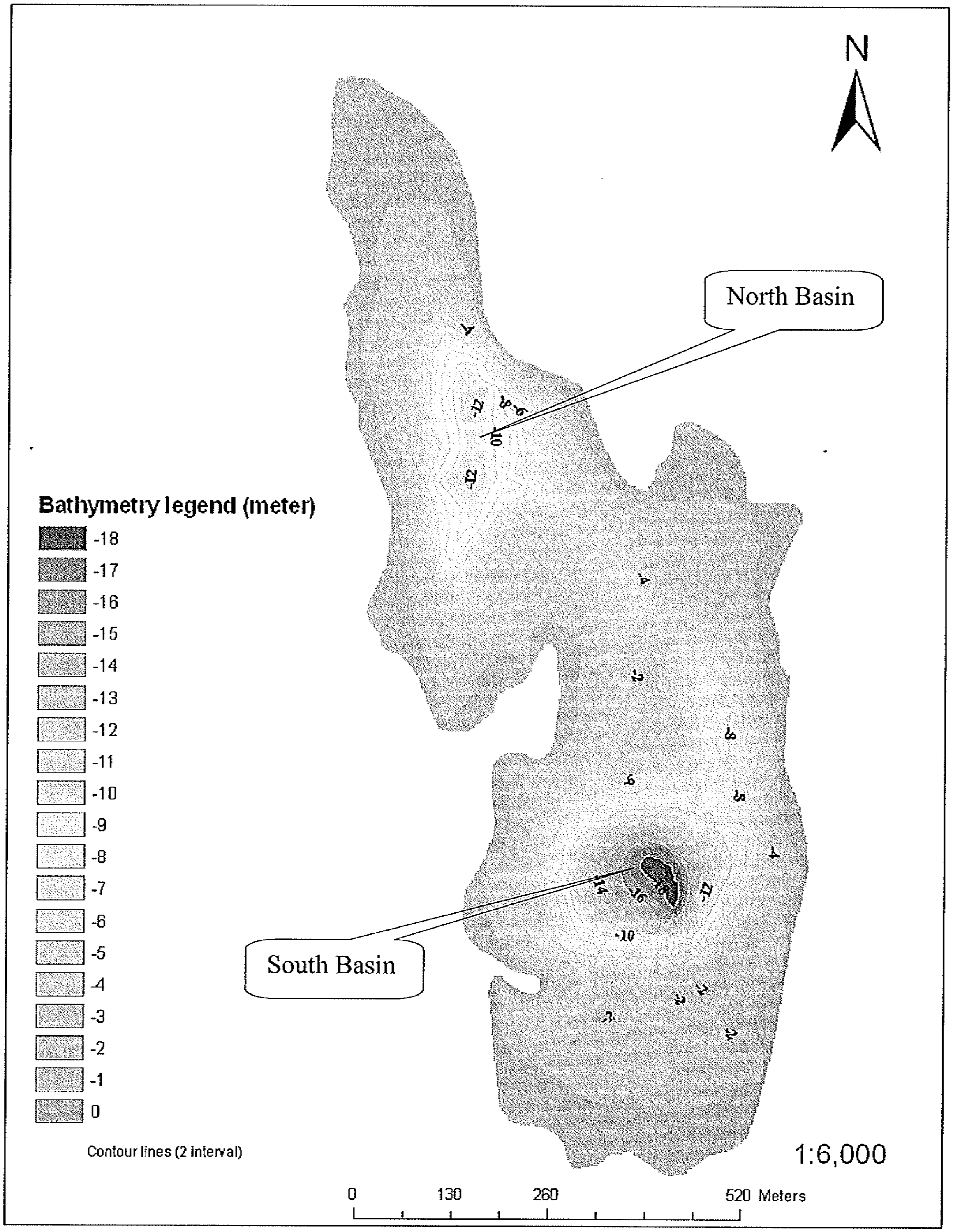

N
North Basin
South Basin
Bathymetry legend (meter)
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
contour lines (4 interval)
1:18,000
0
490
980
1,960 Meters

Figure 17. Bathymetry of Wormy Lake
There are two deeper basins with the deepest part of the lake in the south basin.


N
North Basin
South Basin
Bathymetry legend (meter)
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
Contour lines (2 interval)
1:6,000
0
130
260
520 Meters

Quantifiable substrate attributes for interpolation

Unlike the bathymetry mapping which was relatively easy to do, developing a comprehensive substrate map was difficult because of the problems with the visual identification of the substrates. First, substrate is a fuzzy concept and consists of a sedimentary mixture of varying particle size found on the bottom floor of a natural water body. Like any spatial entity, the measurements include the weight, length, width, height, shape, physical state, dimensions, etc. No single physical unit can cover all of these measurements even if the substrate is more uniform sediment, such as rock or hard clay. However, in a spatial context, it is possible to demonstrate that the hardness and the roughness can be digitized by acoustic ground discrimination systems (AGDS). This acoustic digitization makes it possible and practical to identify the substrate characteristics in an unsupervised classification (i.e. without ground truth). Consequently, the different physical substrate types can be characterized with non-spatial attributes (Class_id and Class name) and covariance matrix eigenvalues (Q values) by a series of cluster algorithms in the QTC IMPACT (Table 3). Second, Class_id is not yet directly interpolated for a substrate map in GIS because this field is an ordinal measurement in an acoustic attribute table. None of the available interpolations using any form of distance weight averaging works directly on the catalogue data for continuous surface analyses in any of the current GIS packages.

According to the cluster algorithms, the Class_id is defined by assigning the distance weighing values on the PCA axes (Q values) to a geo-referenced point in the QTC IMPACT. Any point tagged by the Class_id is positioned in the Q dimensional space (Figure 18). The first three axes (Q1, Q2 and Q3) accounted for 90-97% of the variance of the 166 QTC variables in which Q1 was the greatest weight (Legendre, P. etc, 2002). In a sense, a series of Q values are regarded as a distance scaling of a Class_id (Table 3). An example of splitting acoustic catalogue data from the Winnipeg River (Numao Lake) clearly illustrates the relationship between the Class_id and the Q values (Figure 19). The variation of the three Q values (Q1, Q2, and Q3) discriminated four acoustic classes using t-test (95% confidence). The Q1 mean values were negative (-2.26459 to -0.1759) and varied with different classes (Figure 19A). The Q2 mean values were positive with a small variation (2.03632 to 2.88429), but were not sensitive to the shift in different acoustic classes (Figure 19B). The Q3 values (-0.6026 to –0.82191) were mostly around 0.70, and were regarded as backscatter or noise information (Figure 19C). Obviously the variation in the Q1 values represents different classes. In spite of this, the Q1 values are not predicted to cover the full characteristic information due to the eigenvalues and thereby indirectly defining the Class_id. Nevertheless, because a Q1 value acts as a distance measurement, it can be interpolated into a continuous areal image by the current GIS surface analytical techniques.

The Q1 based continuous areal data can be classified into discrete patterns with arbitrary Q1 value breaks. As a rule of thumb, the legitimate number of Q1 value breaks is determined by the optimal split number (in the QTC IMPACT) of acoustic classes. A further assumption is that natural substrate distributions have clear boundaries. However, there are no clear boundaries among natural substrates as the interface is usually gradual in most cases. Some patterns discretized by the Q1 values can underestimate the true variation of the substrate types, and therefore are wrongly tagged or omitted without the correspondent acoustic classes in space (Figure 20).

In order to illustrate the natural situation, the classification maps of substrate are graded from one to the other with regard to the adjacent substrate classes. Shades of gray fit well with the same areal discrete pattern legend as long as the acoustic classes really depict the characteristics of the river/lakebed (Figure 21). Finding an objective way to decide on and to ground truth the appropriate numbers of the acoustic classification is very important.

The approach that was used in this thesis was to optimize the acoustic classes (split in QTC IMPACT) and to generalize the benthic substrate types (using visual examination and sieving in a benthic sample). The significance of this approach is that the hardness and the roughness of the bottom floor (as indirectly defined by the Q1 values) are determined by the dominant sediments (as a percentage). The variation of the Q1 values is predictably correlated with the percentages of the dominant sediments (Table 13).

Figure 18. Acoustic catalogue data in Q space
Three acoustic classes were split in the QTC IMPACT for the Red River upstream of the Floodgates

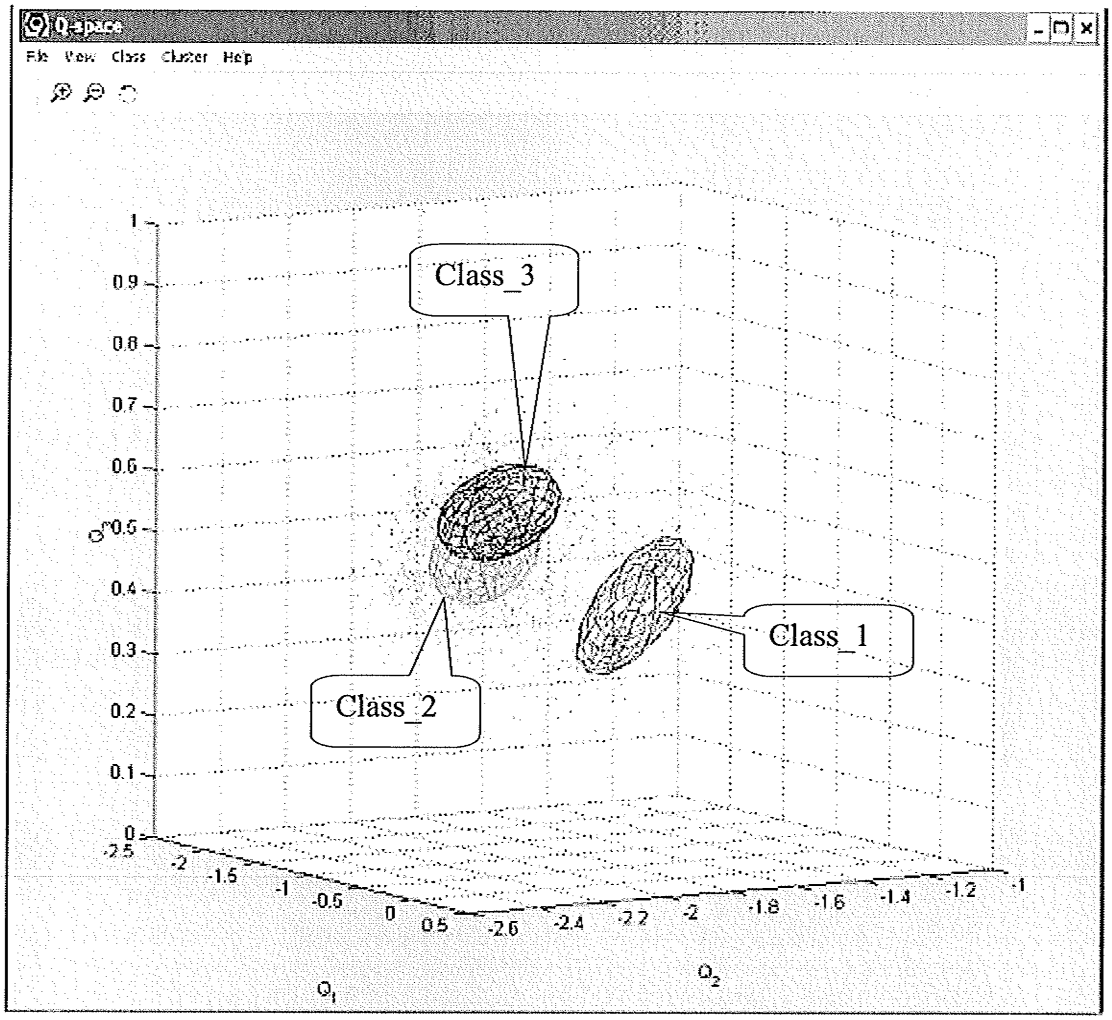
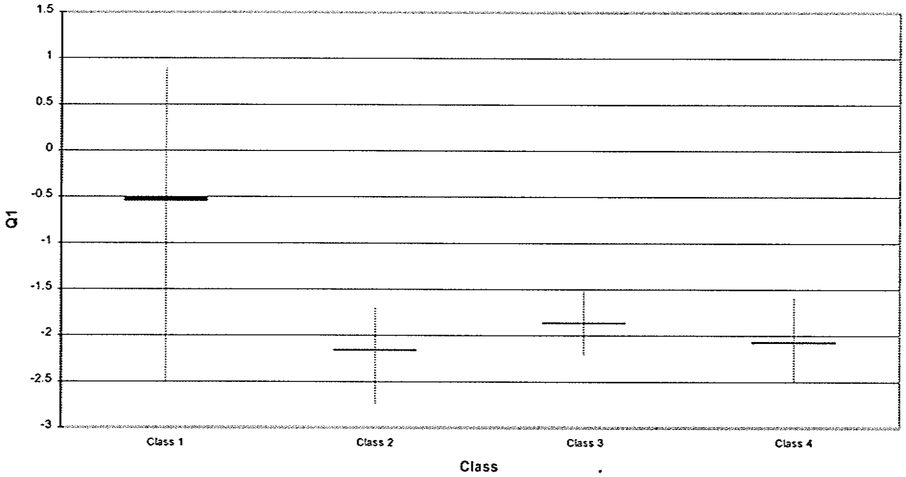
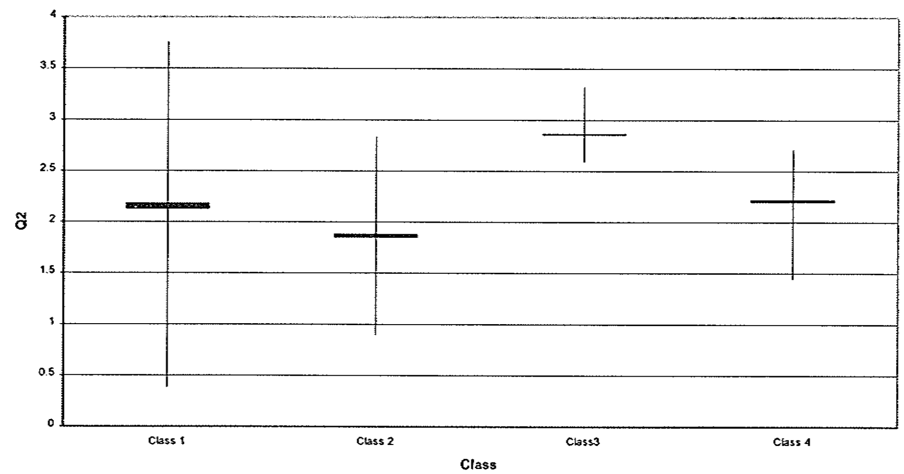

Q-space
File View Class Cluster Help
Class_3
Class_1
Class_2
Q_3
Q_1
Q_2

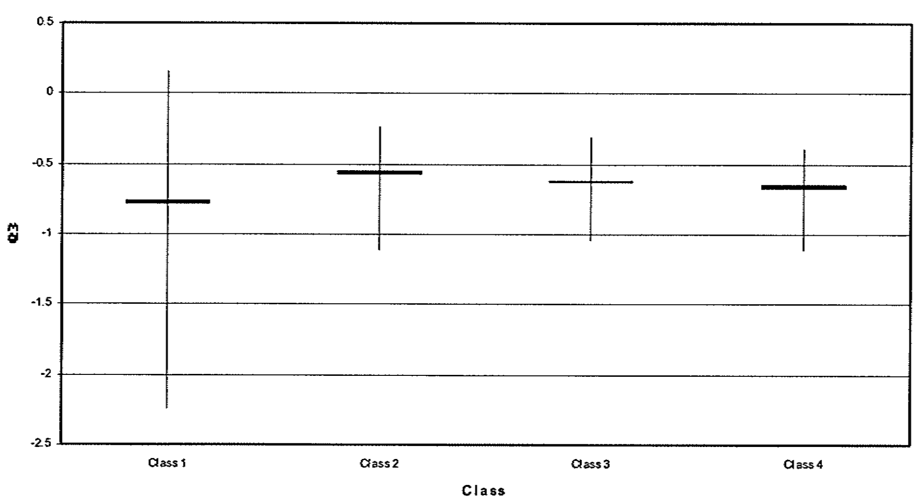
Figure 19. Variation of the three Q values for four acoustic classes from Numao Lake
Horizontal bar: the range from the lower confidence limit (5%) to the upper confidence limit (95%)
Vertical bar: the range from the maximum value to the minimum value
A: Q1
B: Q2
C: Q3


1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
Q1
Class 1
Class 2
Class 3
Class 4
Class

A

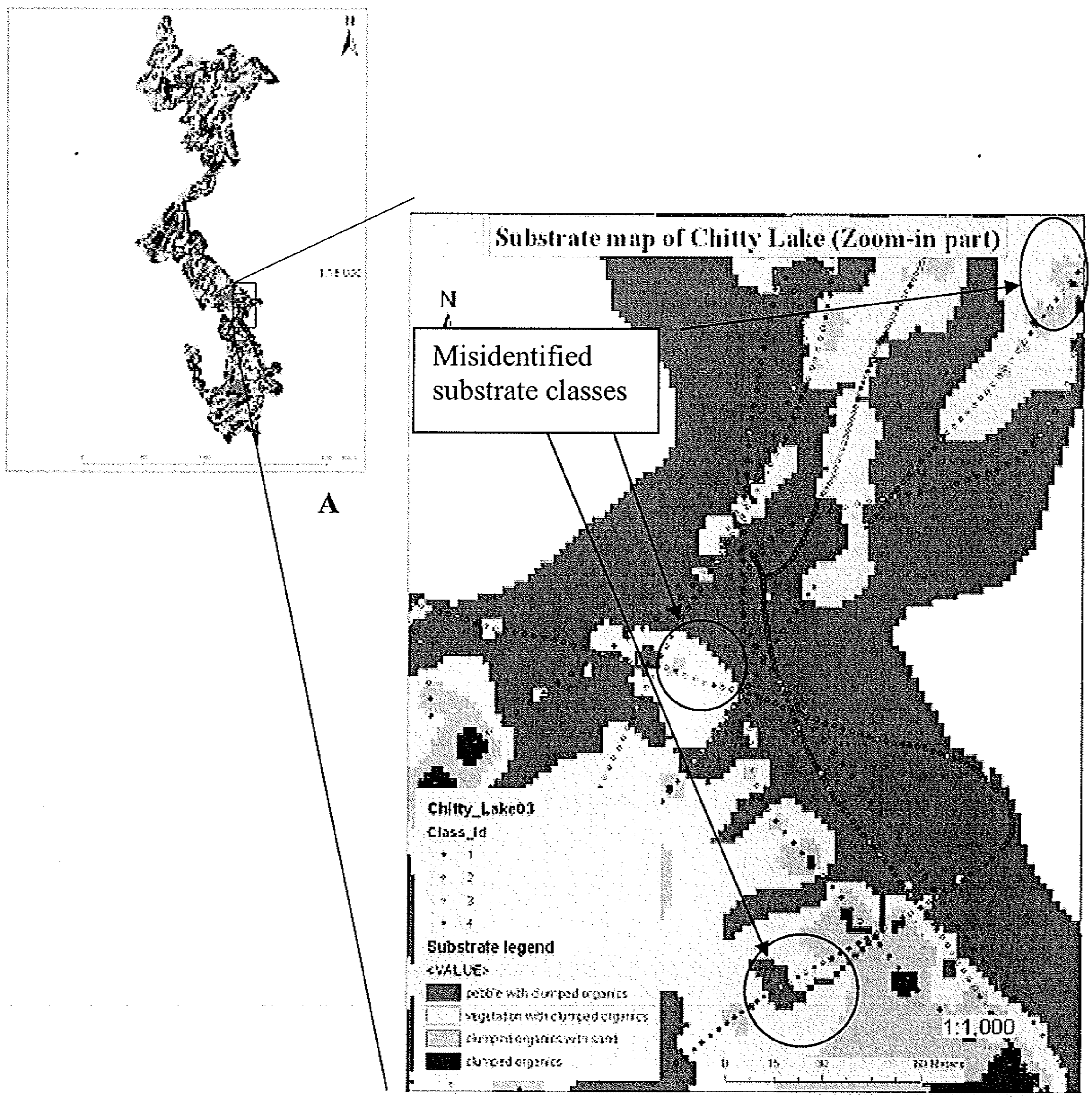

4
3.5
3
2.5
2
1.5
1
0.5
0
Q2
Class 1
Class 2
Class3
Class 4
Class

B


0.5
0
-0.5
-1
-1.5
-2
-2.5
Q3
Class 1
Class 2
Class 3
Class 4
Class

C

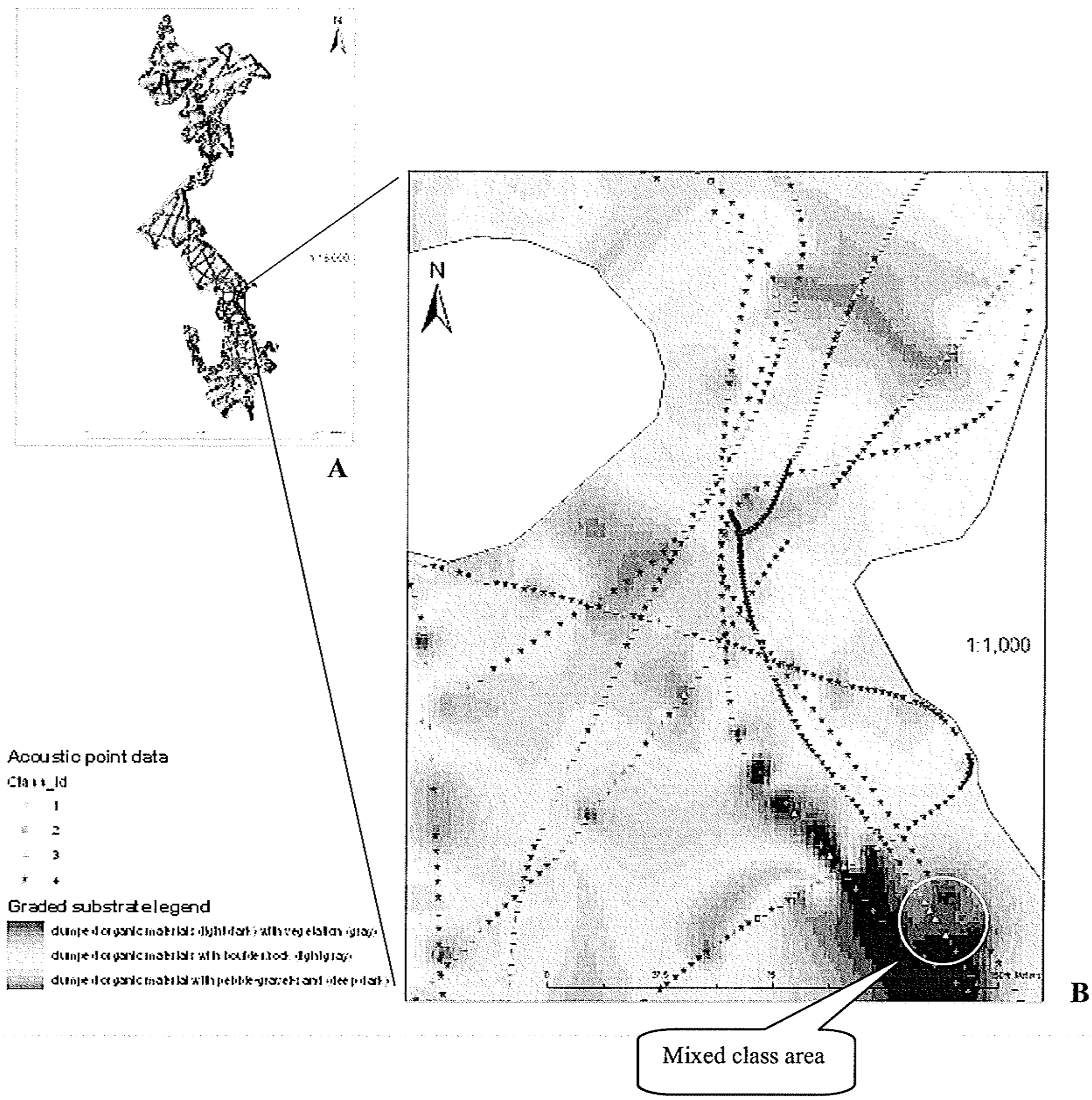
Figure 20. Discretized fitness between the verified acoustic classes and the areal substrate patterns of Chitty Lake (A)
Rectangle: Region of Chitty Lake enlarged in B
Circles refer to acoustic classes misidentified within a discretized areal substrate pattern.


Substrate map of Chitty Lake (Zoom-in part)
N
Misidentified substrate classes
Chitty_Lake03
Class_Id
1
2
3
4
Substrate legend
<VALUE>
pebble with clumped organics
vegetation with clumped organics
clumped organics with sand
clumped organics
1:1,000
0 15 30 60 Meters

A

B

Figure 21. Graded fitness of the verified acoustic classes and areal substrate patterns of Chitty Lake (A) Rectangle: Region of Chitty Lake enlarged in B. Circles refer to acoustic classes misidentified within a graded areal substrate pattern.


N
A
N
1:1,000
B
Mixed class area
Acoustic point data
1
2
3
4
Graded substrate legend

Optimal acoustic classification and ground truth

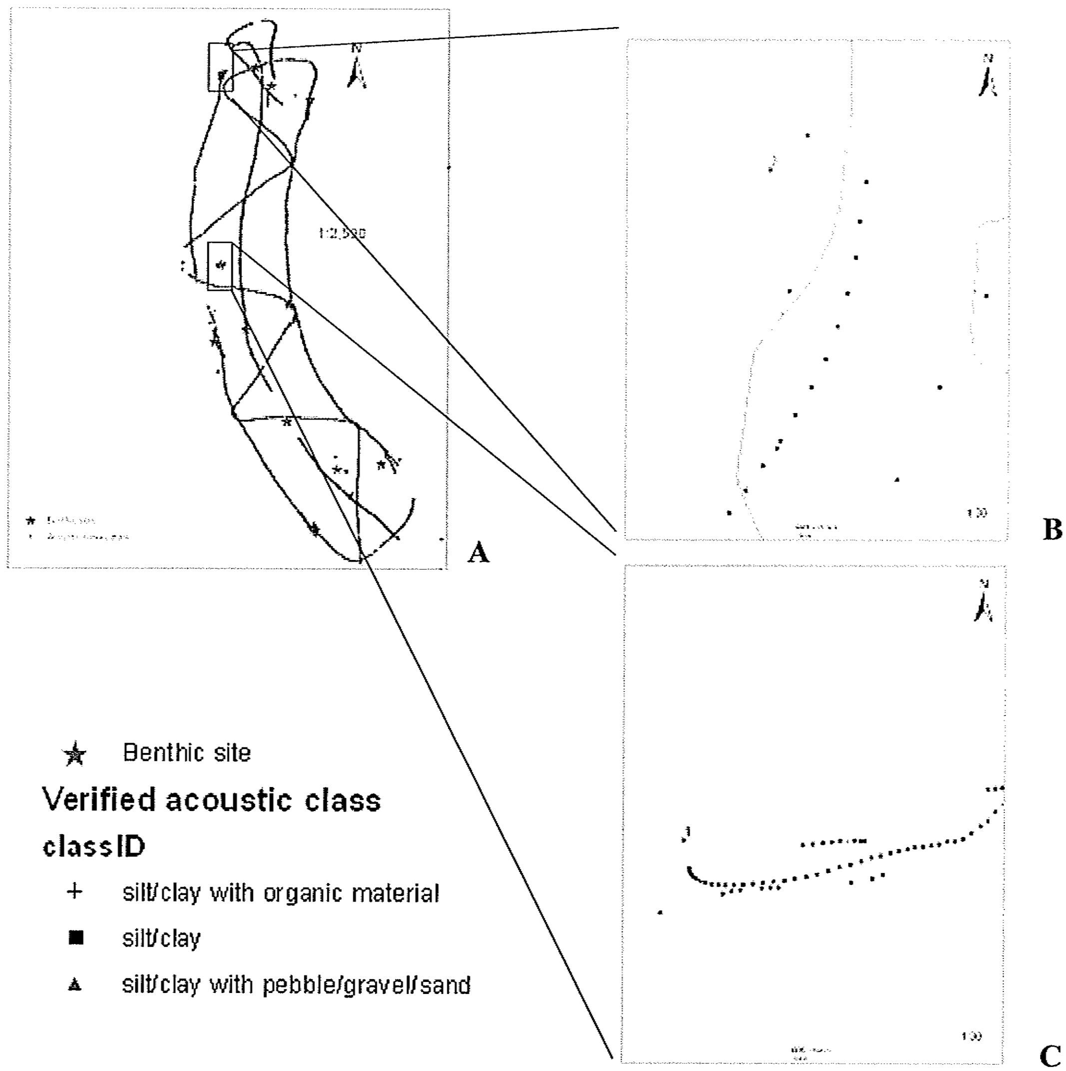
The acoustic data, in theory, can be split repeatedly to define the classes. A benthic sample can also be sieved and selected by the grain-size of a sediment sample. However, The Q1 values of an indirect measurement and the limitations of spatial resolution restrict the arbitrary number of acoustic classes and sedimentary types. In practice, too many acoustic classes make ground truth very difficult and cannot be verified by benthic grabs as the amount of time required would be prohibitive. In some cases, it is also impossible to verify a corresponding acoustic class even if a more detailed sediment classification is available. For example, since silt and soft clay could not be discriminated, based on the splitting of acoustic classes, the two types of sediments were combined and classified as silt/clay in this project.

Clearly, there needs to be a strategy on how to optimize the acoustic classes and correlate the benthic sediments in order to generalize the substrate types. As mentioned in the Method and Materials section, an acoustic classification was undertaken in the Cluster of QTC IMPACT. The CPI was recommended for optimizing acoustic data splits by combining one or two dominant types into a substrate class.

An exception to generalized substrate classes needs an additional comment. The bottom patches sometimes contained vegetation at 10-20 % per sample and affected the substrate characteristics. When a sediment type constitutes a very high proportion of a sample, it does not correlate well with the acoustic signal. For example, a sample consisting mostly of pebbles and cobbles was collected with a benthic grab at Site 1 and Site 7 above the Red River upstream of the Floodgates (Figure 22), but the homogeneous acoustic signals for two sites indicated the area was comprised of silt/clay. The pebble and cobble sink into the soft silt/clay so that they contributed very little to either the hardness or the roughness of the surface. Consequently, ground truth is important and caution is advised when the interpreting is based on the Q values only.

Regardless of what a benthic sample indicates, an experienced researcher prefers to split the acoustic data into three groups, prior to correlating the acoustic signal and the benthic sample. A decision can then be made if further splitting of the data is required.

Figure 22. Benthic samples which are not well correlated with acoustic signals on the Red River upstream of the Floodgates
A: Acoustic and benthic survey areas (See Figure 2 for orientation)
B: Site 7
C: Site 1


N
1:2,500
A
B
C
Benthic site
Verified acoustic class
classID
silt/clay with organic material
silt/clay
silt/clay with pebble/gravel/sand

The most conservative approach is to correlate acoustic classes with the number of benthic substrate types. Occasionally additional splitting, i.e. more than three levels, is helpful to confirm or to explore the substrate types such as bedrock or hard clay which can not be collected with benthic grabs. Three classes were split in terms of the CPI (Cluster Performance Index) (see P48 for details) for acoustic data from the Red River upstream of the Floodgates, but only two were verified: silty clay, and silty clay with organic materials. Pebble/gravel was rarely verified from samples along the acoustic tracks. The locations of this acoustic class were too infrequent to be targeted by grabs. It was probed as cobbles and pebbles with silty clay with a long pole (Figure 23). In the end, three substrate types could be classified based on their sediment composition, roughness and hardness (Table 11).

Acoustic data from Numao Lake (Winnipeg River) were split into four classes (Figure 24) according to the CPI (see P48 for details). Unlike the region upstream of Floodgates, the substrate classes in the Winnipeg River are likely to have more acoustic classes. The benthic samples were collected at 39 sites in the Numao Lake and 25 sediment samples were collected. The classes were identified as bedrock, cobble/pebble/gravel, and mixed sand, mixed sand with organic materials. Mixed sand and mixed sand with organic materials were confirmed directly from the sediment samples. Bedrock was "interpreted" because the Ponar grab was unable to pick up any sediment and the sample collection was done over known bedrock areas. Cobble/pebble/gravel was obtained infrequently as they were located in pockets between large rocks and boulders and especially near strong currents (Table 12). The Seven Sisters site, downstream of Numao Lake, had a similar geology and it was assumed that the overall sediment composition should be generally similar. However, specific percentages of the dominant sediment types (i.e., a series of grain size sands) varied due to the different local hydrologies (Figures 24, 25).

The distributions of the substrate types in the Red River (Floodgates) and the Winnipeg River (Numao Lake) were characterized by the hydrological conditions. Coarse sediments were usually found in deeper central areas where the currents were faster and soft sediments were found near the banks and shallow areas where the flows were slowed.

Figure 23. Three acoustic classes for the Red River upstream of the Floodgates
The distribution of three acoustic classes from the Red River upstream of the Floodgates. The cross tracks verify that a similar acoustic signal was recorded from most points on the riverbed.

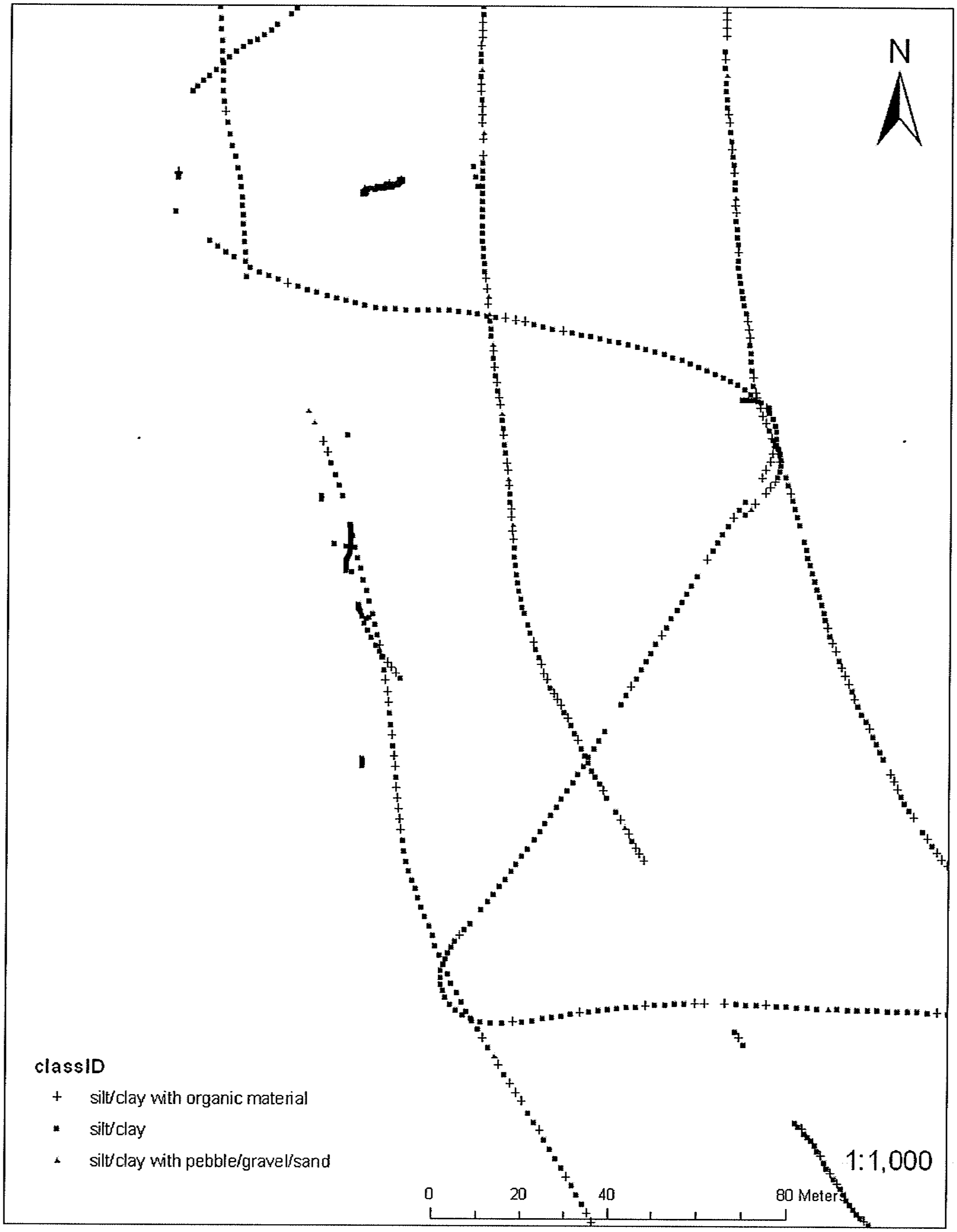

N
classID
+ silt/clay with organic material
silt/clay
silt/clay with pebble/gravel/sand
1:1,000
0
20
40
80 Meters

Table 11 Sediment classes of the Red River upstream of the Floodgates* **(Percent: %)**

Sediments / Substrate classes	Rock	Pebbles	Gravels	Sands	Organic	Clay/silt	Sampling site
Coarse sedimentary and silty clay	0	0-90	2-35	1-10	0	10-85	1 3 5 7
Silty clay	0	0	0-3	0-5	0	94-99	2 4 6
Organic and silty clay	0	0	0	0-2	0-2	96-98	8 9 10

* Proportion is verified by weighing each component of a benthic sample using the sieving classification

Figure 24. The distribution of four acoustic classes of Numao Lake, the Winnipeg River Cross tracks verify that a similar acoustic signal was recorded from some points on the riverbed.

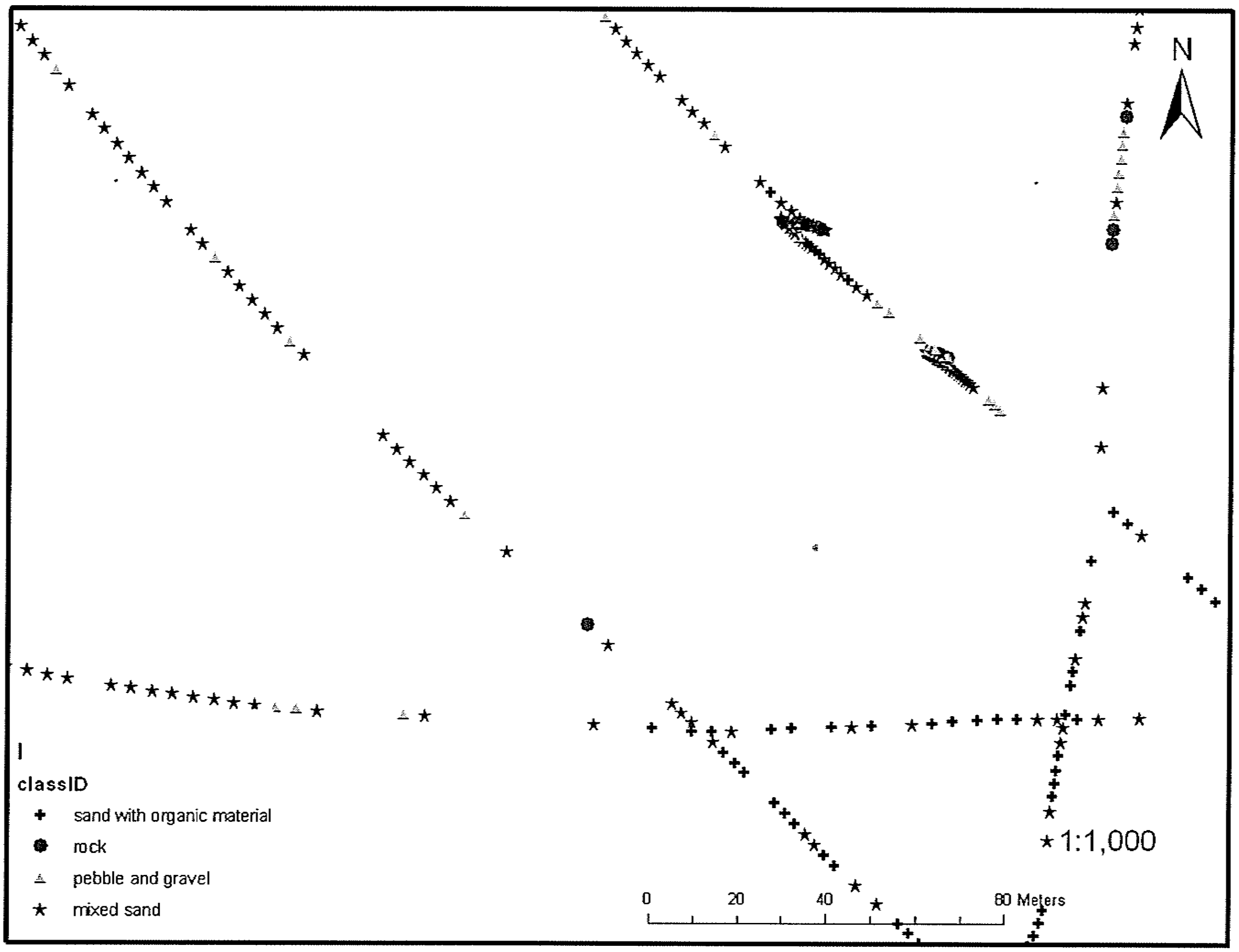
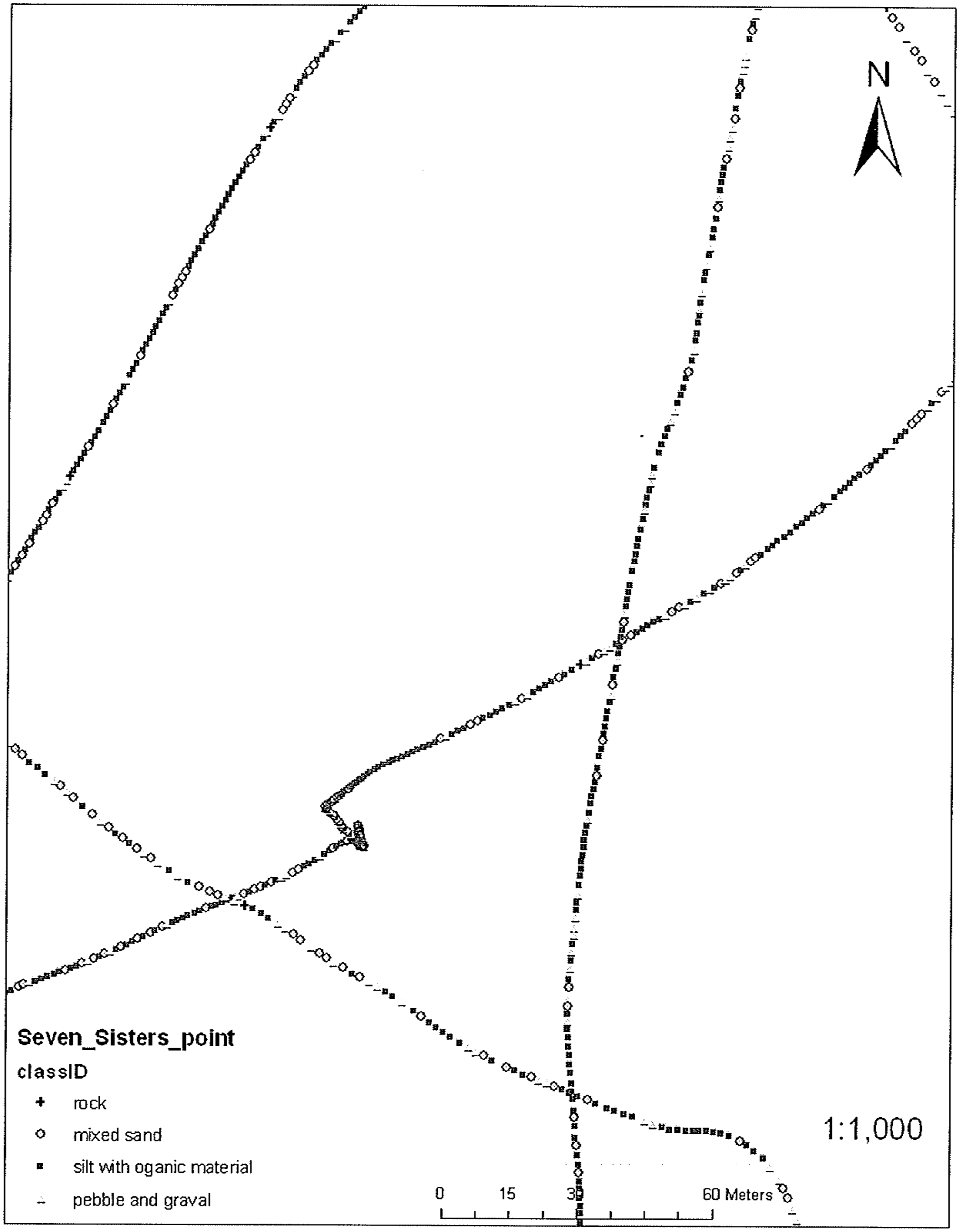

N
classID
sand with organic material
rock
pebble and gravel
mixed sand
0
20
40
80 Meters
1:1,000

Table 12 Sediment classes of Numao Lake, the Winnipeg River* (Percent: %)

Sediments / Sediment Classes	Rock	Hard clay	Gravel	Sands	Clay/silt	Sampling site
Rock	90	0	0-5	0-5	0	5 16 38 39
Coarse sands	0	5-10	50-60	20-25	0-5	1 15 19 37 35 36
Sandy/organic silt	0	0	0	20-30	70-80	10 14 20 21 23 24 27
Silty sands	0	0	0-5	70-80	10-15	2 3 5 6 7 8 9 11 12 13 17 18 22 25 26 28 29 30 31 32 33 34
Fine sands	0	0	0	20-30	70-80	4

* Proportion is verified by weighing each component of a benthic sample based on the sieving classification

Figure 25. The distribution of four acoustic classes of Seven Sisters, the Winnipeg River Cross tracks verify that a similar acoustic signal was recorded from some points on the riverbed.


N
Seven_Sisters_point
classID
rock
mixed sand
silt with oganic material
pebble and graval
0
15
30
60 Meters
1:1,000

Eight regions were surveyed acoustically from the Great Bear River down to the Horseshoe Bend along the lower Mackenzie (Figure 4B, P30) and 25 benthic samples were collected. The acoustic data was split into three major classes in these regions, but the distribution of a dominant class varied with each region. For example, bedrock frequently appeared at Great Bear (Figure 26) while it was rarer downstream, and was not found in the benthic samples at the survey area of Horseshoe Bend (Figure 27).

The verification algorithm of acoustic classes from Chitty Lake and Wormy Lake were similar. Four levels of class splitting were optimized according to the CPI and were verified by "Visual Classification". Most of the benthic samples were comprised of clumped organic materials, but often after drying these samples, they appeared as unnaturally consolidated size fragments, reconstituted from the sieving material. The results were inconsistent with the visual inspections. In these cases, it was better to use the visual method, although it was less precise. The four basic sediment types identified: organic material, silt, gravels and rock (Figures 28, 29).

Four acoustic classes (Class 1 -- clumped organic materials, Class 2 –clumped organic materials with sand/gravels, Class 3 –clumped organic materials with vegetation, Class 4- clumped organic materials with cobbles/rocks) were verified from Chitty Lake with the generalized substrate types. Except for rock, boulder and big cobbles, 18 benthic samples were sorted out into Class 1, Class 2 and Class 3 based on the proportion of the major components of each sample (Figure 30). The differences between Class 2 and Class 4 were dependant on the grain size changes that ranged from sand to rocks. Similar results were obtained for Wormy Lake where the verified classes were: Class 1-clumped organic materials, Class 2- clumped organic materials with gravel-pebble, Class 3-clumped organic material with boulder/bedrock, Class 4-clumped organic materials with vegetation. The exception was in the deep zone in the north basin of Chitty Lake where the acoustic signals might have behaved differently. There are at least three possibilities: thermal stratification; bubbles generated by springs (Wright, D. J., 2002) or fluidized organic substrate (freeze drying this material found it contained up to 90% water in situ) which suggests it may not be dense enough to send a consistently high quality acoustic signal.

Figure 26. The distribution of three acoustic classes in Great Bear River, the Mackenzie River
Cross tracks verify that a similar acoustic signal was recorded from some points on the riverbed.

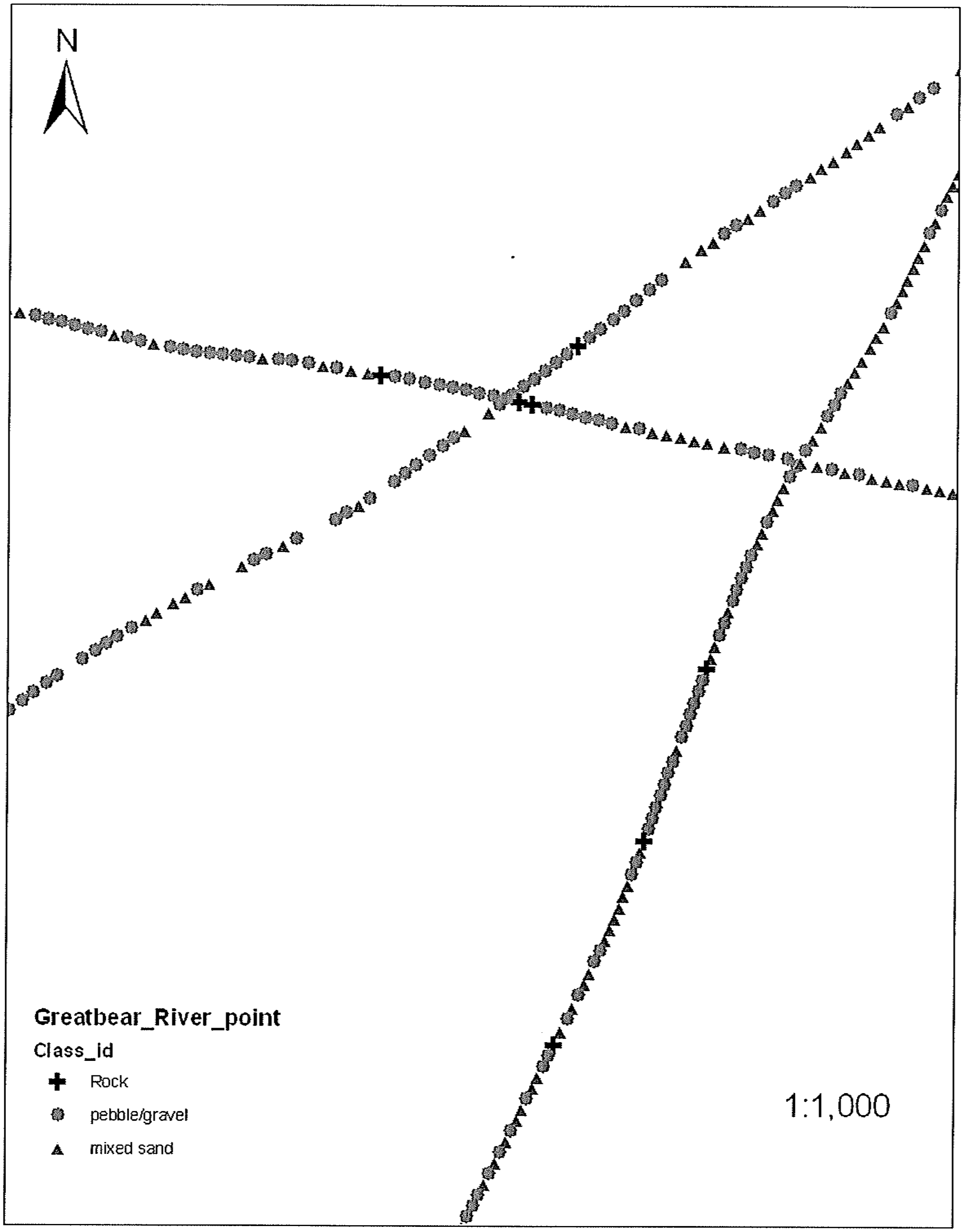

N
Greatbear_River_point
Class_id
Rock
pebble/gravel
mixed sand
1:1,000

Figure 27. The distribution of three acoustic classes in Horseshoe Bend, the Mackenzie River
Cross tracks verify that a similar acoustic signal was recorded from some points on the riverbed.

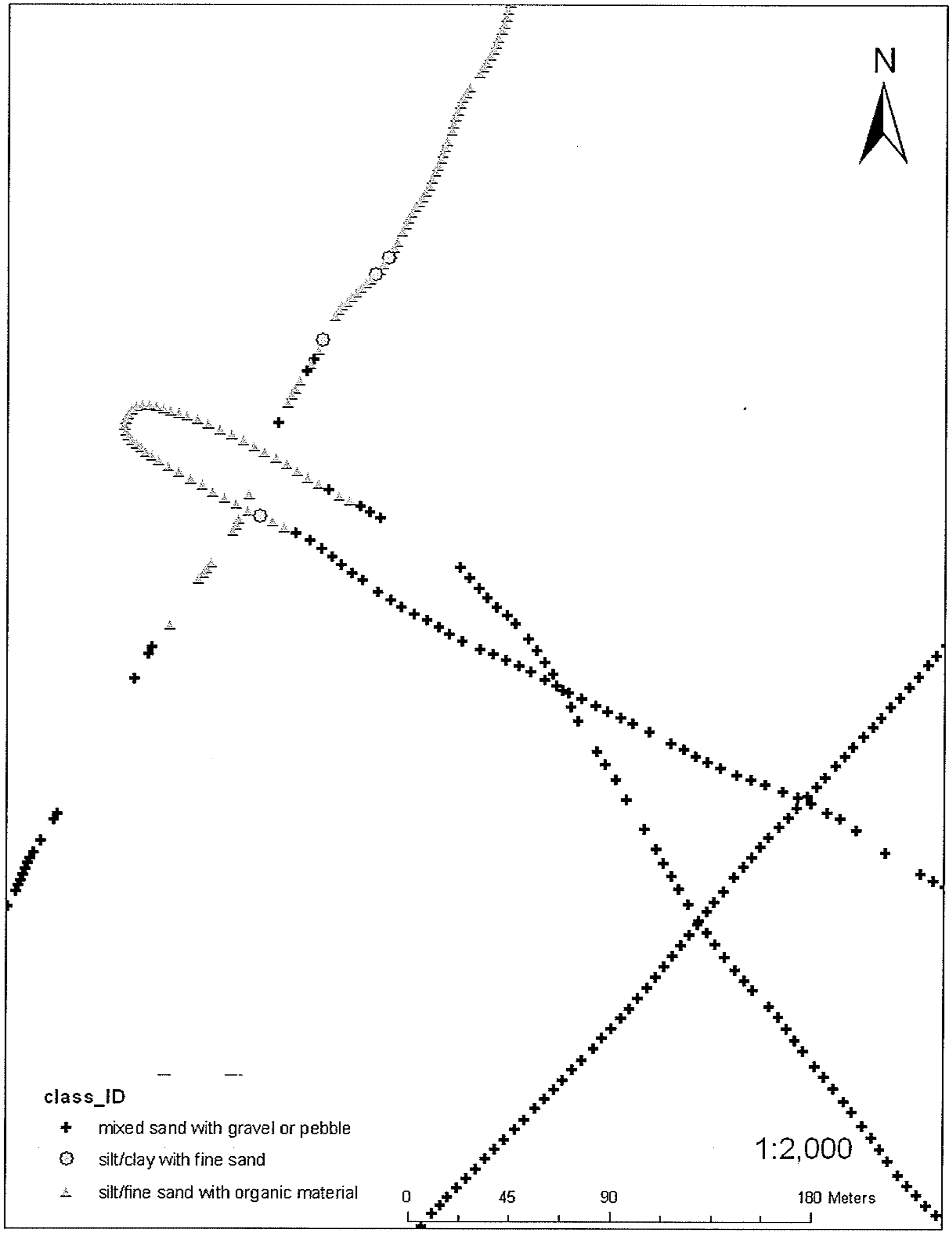

N
class_ID
mixed sand with gravel or pebble
silt/clay with fine sand
silt/fine sand with organic material
1:2,000
0
45
90
180 Meters

Figure 28. The distribution of four acoustic classes in Chitty Lake
Cross tracks verify that a similar acoustic signal was recorded from some points on the lakebed.

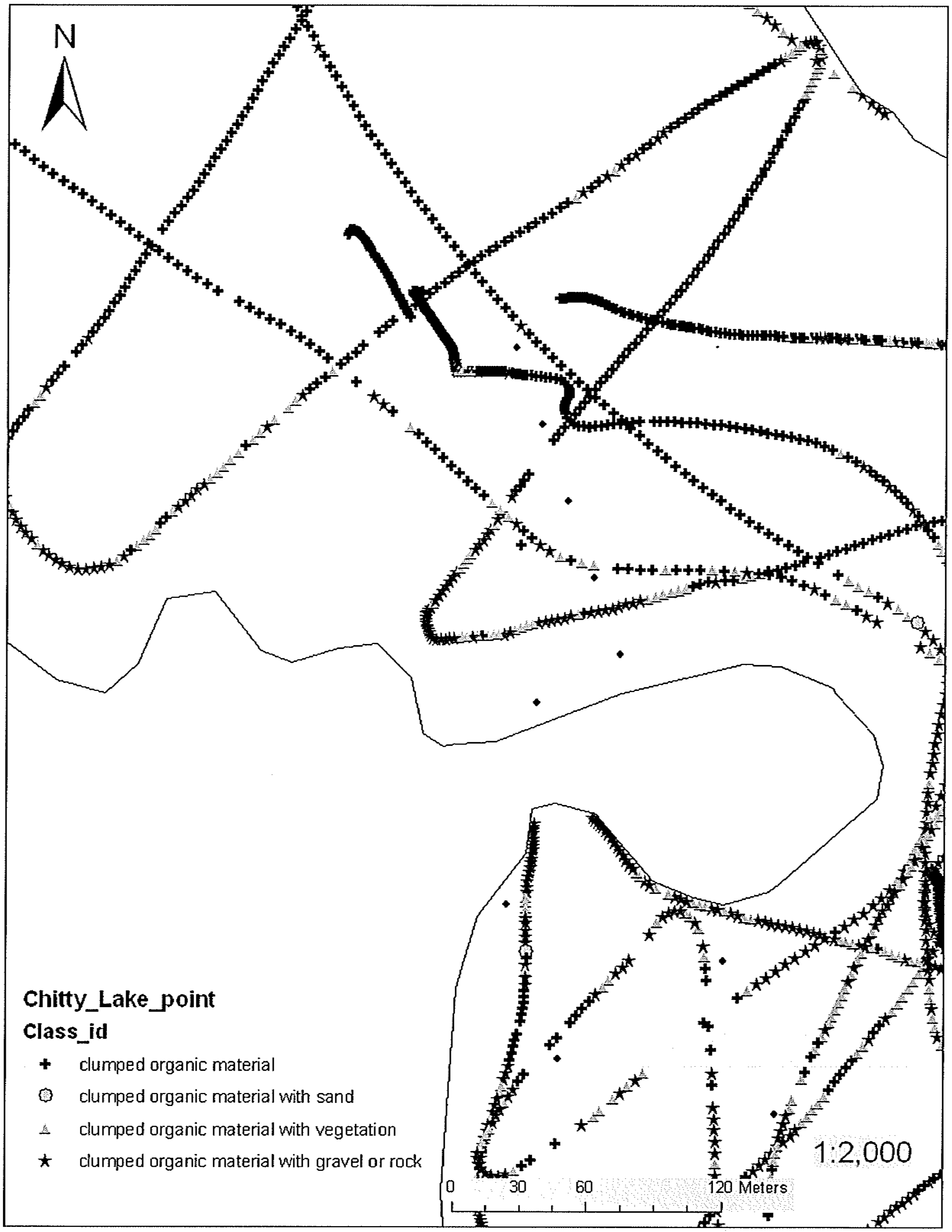

N
Chitty_Lake_point
Class_id
clumped organic material
clumped organic material with sand
clumped organic material with vegetation
clumped organic material with gravel or rock
0
30
60
120 Meters
1:2,000

Figure 29. The distribution of four acoustic classes in Wormy Lake
Cross tracks verify that a similar acoustic signal was recorded from some points on the lakebed.

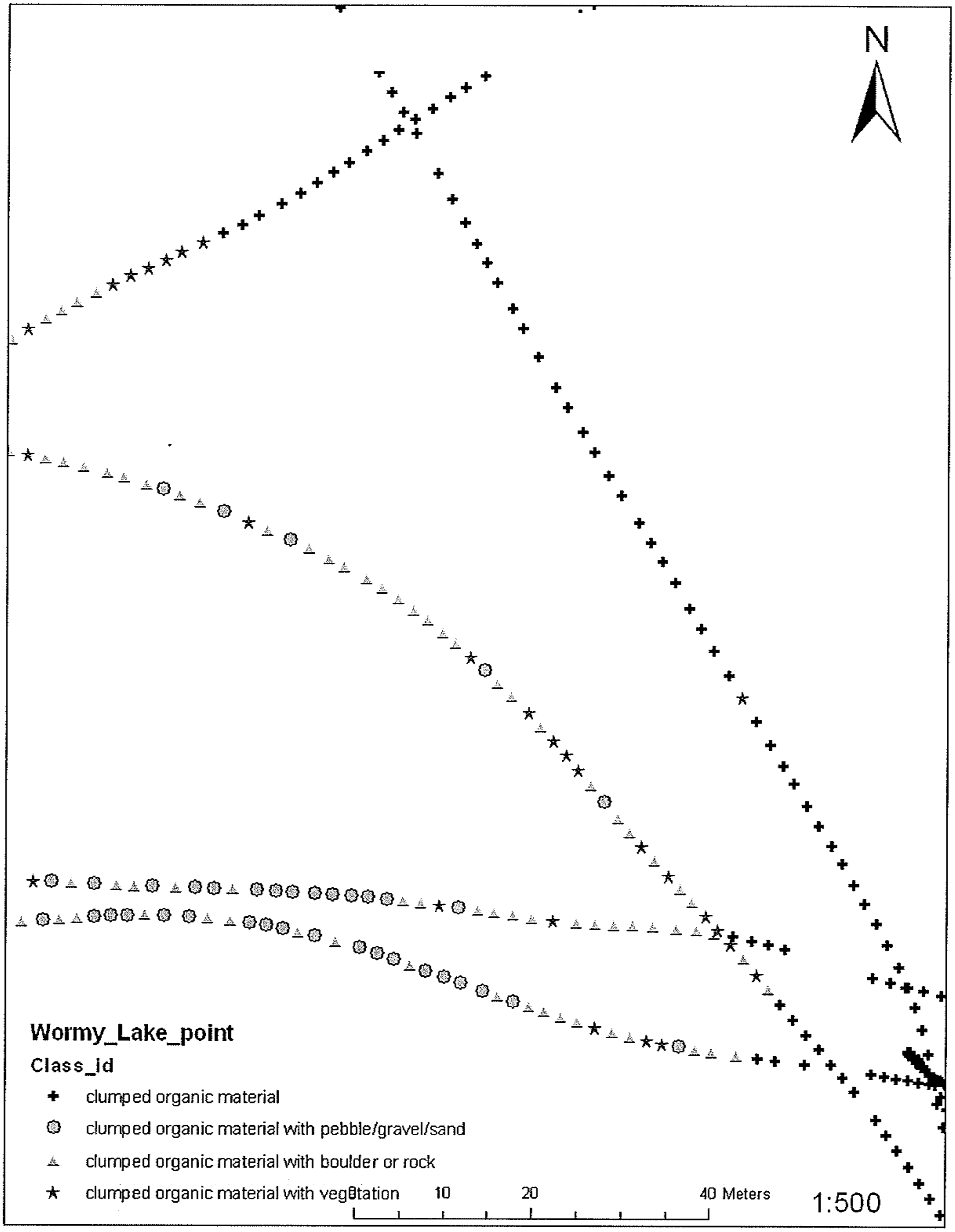
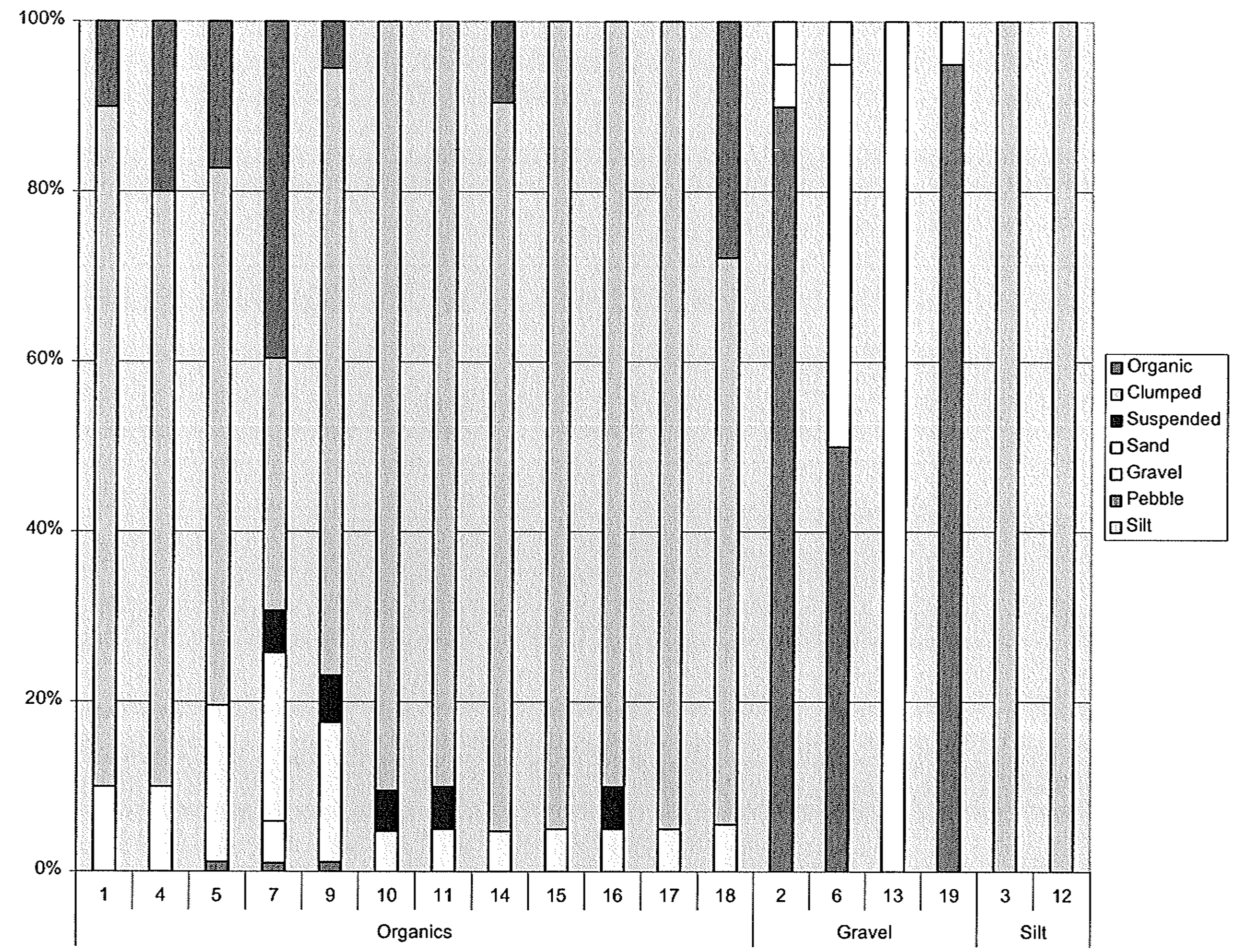

N
Wormy_Lake_point
Class_id
clumped organic material
clumped organic material with pebble/gravel/sand
clumped organic material with boulder or rock
clumped organic material with vegetation
0
10
20
40 Meters
1:500

Figure 30. Proportion of the substrate types as a percent based on the "Visual Classification" of the substrates from Chitty Lake
The X axis is labeled with the sampling ID number (18)


100%
80%
60%
40%
20%
0%
1
4
5
7
9
10
11
14
15
16
17
18
2
6
13
19
3
12
Organics
Gravel
Silt
Organic
Clumped
Suspended
Sand
Gravel
Pebble
Silt

Variation of Q1 value vs. types of physical substrate

It was important to determine if the acoustic classes produced by the QTC IMPACT (i.e., Q values correlated to substrate types) were correlated with the substrate types. For example, it is reasonable to speculate that the bedrock or hard clay from different water systems should share similar characteristics (i.e., Q values). If so, the values will be directly applied to other survey areas even if the ground truth was not done (i.e., Ponar grabs to verify the acoustic classes).

The Q values were computed from a covariance matrix for ordination and without physical dimensions (Legendre, 2002). Mathematically, the Q values are eigenvalues and represent the distances among records (pings) in multi-ordination space. The eigenanalysis illustrates that a high positive distance indicates a positive correlation between the ordination axis (Q axis) and a given variable (an echo shape and spectral characteristic variable) while a high negative distance indicates a negative correlation. Values at or near zero, on the other hand, indicate that a given variable with a zero on the Q axis has no direction (Kenkel, 2003).

As the Q1 values were negative values and varied with the different classes, the homogenous degree of substrate distribution could determine the Q1 value variation. When the overall bed of a water body was comprised of a soft dominant substrate type such as clumped organic materials and the hardness and the roughness was based on other components (sand, pebble or silt.) that were embedded or mixed, the Q1values for the dominant substrate types were lowest (i.e., Chitty Lake). Also, the Q1 values were similar if the substrate distribution of a bottom patch changed gradually (i.e., the Delta of the Mackenzie River). This always occurred in the river systems that had obvious currents in a single direction. By contrast, the obvious substrate patterns were distributed in the water bodies with slow flow or no flow at all and there were quite the discrete Q1 values for different substrate types (Chitty Lake and Wormy Lake) (Table 13).

When Q1 were similar in Wormy Lake and Falcon Lake, the substrate types was also similar, i.e. pebble or sand or rock. Small differences were noted in the values for the clumped organic materials and presumably, this was due to the varying percentages of a sediment type in the substrate i.e. silt vs. clay or varying amounts of water in the organic layer (Table 13). Surprisingly, the differences in the Q1 values were noted for the same type of substrate among the three rivers, even between the two sections of the Winnipeg River (Numao Lake and Seven Sisters). For example, many bottom substrates in three rivers were identified as bedrock, but the Q1 values ranged from -0.18 (Numao Lake) to -1.045 (Great Bear River). Based on these observations, the application of the shared features of verified acoustic catalogues should be viewed with caution. For similar distribution patterns of substrates in a system like that of the Mackenzie River, it is necessary to select homogeneous substrate patches, and to correlate their acoustic data over these places with the corresponding substrate types, and then apply them to the similar type of sites in the other survey sections.

Maps depicting substrate patterns

The goal of displaying broad scale substrate patterns can be fulfilled spatially by interpolating the continuous surface of a river/lakebed in terms of the Q1 values. The process relies on the variation of the Q1 values that are correlated to the sedimentary characteristics. Topogrid uses an iterative finite difference interpolation technique. This technique combines 'local' interpolation methods such as the inverse distance weighted (IDW) in computational efficiency with global interpolation methods such as kriging and splines without losing the surface continuity. However, if Topogrid interpolation is to be used, an appropriate grid size needs to be established. Consequently for this project, there was a tradeoff between the larger scale visualization of the substrate types and the finer scale local examination by benthic sampling. For example, a benthic weight could be accurate to 0.1 gram for grain-size sediments grabbed at about 15-20 square centimeters, but a minimum grid size or resolution (2 meters in length) for interpolating the Q1 values is required due to selection of different map scales and the efficiency of pix computations. It is this grid size that represents the characteristic of a substrate type on a broad scale map, but the same area contains detailed information on the sediment distributions from the perspective of benthic sampling analysis. That means that the thematic details could be lost depending on the grid size that is selected. Consequently, it is unrealistic to assume a high degree of accuracy for each sediment composition and for each distribution at a fine analytical level on a large scale map. Furthermore, there are no significant values on substrate maps to display the different sediments on a coarse scale map. There is a need to compromise between the optimization of acoustic classes and the scale of the dominant substrates by setting a standard grid size or resolution for interpolation.

In summary, a comparison of the acoustic signals with the actual benthic samples allows the following generalization using a Topogrid interpolation. In the case of river systems such as the Mackenzie River, the Winnipeg River and the Red River, the conclusions concerning a common catalogue of acoustic signals and substrate types is less clear. There were 21 sections that were verified directly for the acoustic classes in the three rivers and 12 sections to be correlated with the verified acoustic classes in the same river. The components and proportions of the benthic samples from these rivers, even from different sections of the same river, varied greatly (Table 13). The main feature or dominant substrate type for each river was explored as follows: silt/clay for The Red River (Figure 31), sand for The Winnipeg River (Figure 32, 33), gravel/sand/silt for the Mackenzie River (Figure 34). In the case of the small Arctic lakes, Chitty Lake and Wormy Lake, the following substrates are similar for both lakes (Table 13, Figure 28, 29). The main feature or dominant substrate type for Chitty Lake (Figure 35) and Wormy Lake (Figure 36) is clumped organic materials.

It is also worth noting that more than one acoustic signal may be interpreted as a single substrate class. For example, two or three similar signals will be interpreted as a mixed substrate (Figure 21).

Table 13 Relationship between the Q1 values of acoustic classes and the benthic substrate type

	Class 1	Class 2	Class 3	Class 4	Class 5
Mackenzie River(1)	-1.37365	-1.81177	-1.163903		
	gravel	fine sand	hard clay		
	70-80	80-90	90		
Mackenzie River(2)	-1.02556	-1.58557	-1.26532	-1.84585	
	hard clay	Sand	pebble	silt	
	80-90	50-60	60-70	80	
Mackenzie River(3)	-1.04462	-1.52884	-1.81002		
	rock	Sand	silt		
	100	90	80		
Numao Lake Winnipeg River	-1.63277	-0.18474	-0.63883	-1.0948	
	organic silt	Rock	pebble	sand	
	20-80	100	20-70	80	
Seven Sisters Winnipeg River	-0.77177	-1.61352	-1.78824	-1.29399	
	Rock	organic sand	sand	pebble	
	100	80	90	80	
The Red River upstream of the Floodgates	-0.688228	-1.25182	-0.21839		
	organic silt/clay	silty clay	pebble		
	90-95	20-95	60-90		
Chitty Lake	-0.67176	-1.63584	-1.34522	-1.81113	
	clumped	Sand	vegetation	pebble	
	80-90	70-80	10	40-50	
Wormy Lake	-1.1834	-2.53388	-2.19449	-1.9402	
	clumped	pebble	rock	vegetation	
	90-100	70-80	100	20-30	
Falcon Lake	-0.82597	-1.49872	-1.93944	-2.44029	-2.22849
	clumped	fine sand	vegetation	pebble	rock
	80	70-80	20	70	100
Stephenfield	-0.9026	-2.04564	-1.65706	-1.99171	
	clay	Rock	silt	vegetation	
	80-90	100	80-90	20-30	

*** Mackenzie River (1) – Mackenzie River from delta to MK10; Mackenzie River (2)– Mackenzie River from Travaillant River to MK22; Mackenzie River (3)– Great bear River of Mackenzie River**
**** clumped – clumped organic materials**

Figure 31. Substrate map of the Red River upstream of the Floodgates
The river bed is predominantly silt/clay with some pebble/gravel and organic matter. Pure silt/clay usually is located in small pockets in the river bed. The pebble/gravel is located in deeper areas and the organic material occurs more frequently in shallow areas.

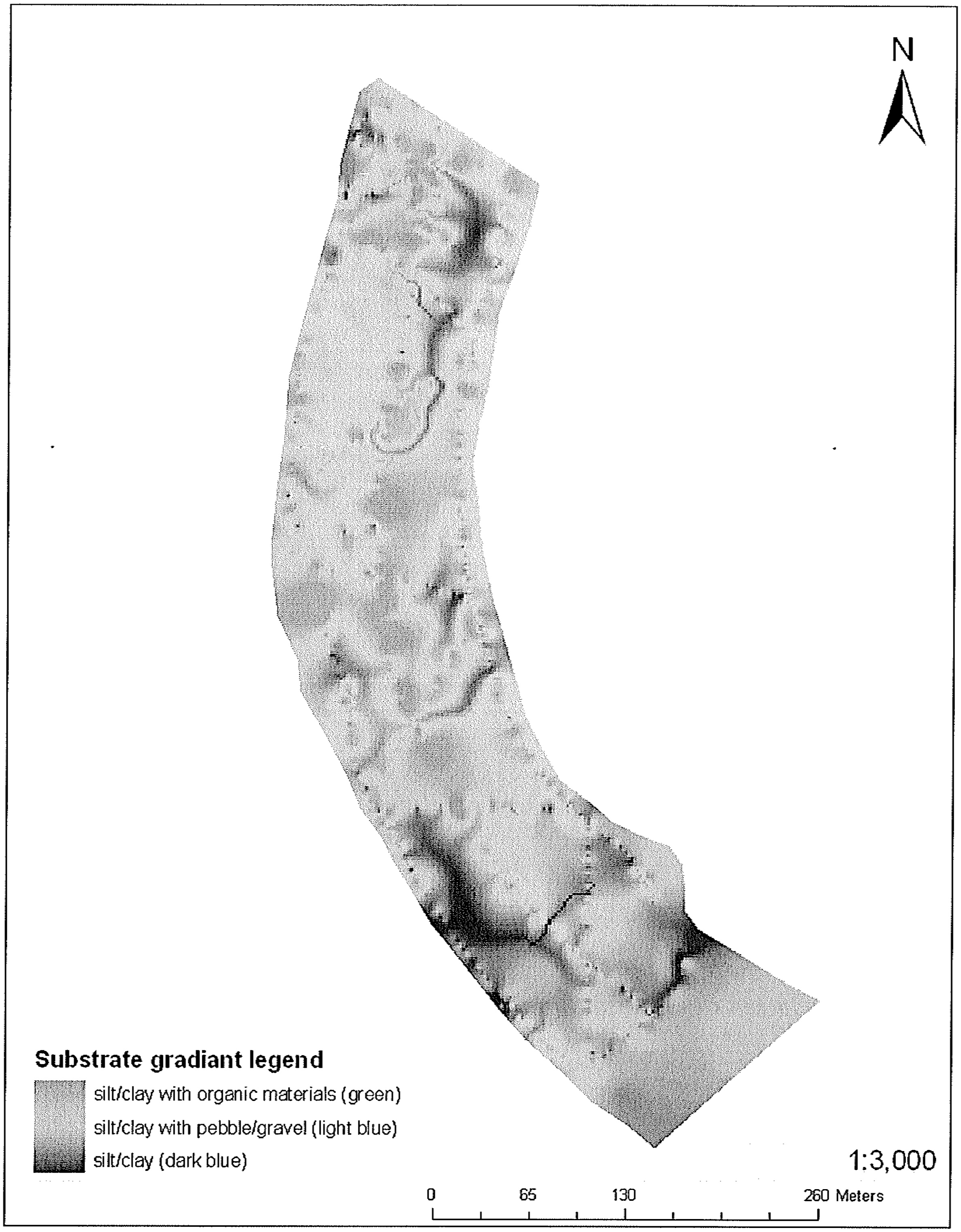

N
Substrate gradiant legend
silt/clay with organic materials (green)
silt/clay with pebble/gravel (light blue)
silt/clay (dark blue)
1:3,000
0
65
130
260 Meters

Figure 32. Substrate map of Numao Lake, the Winnipeg River
There are four substrates, but sand is the most common substrate. Rock is mostly located in the deep areas with a rapid flow. The pebble/gravel is more distributed along areas with a faster flow. The organic material is often near the bank.

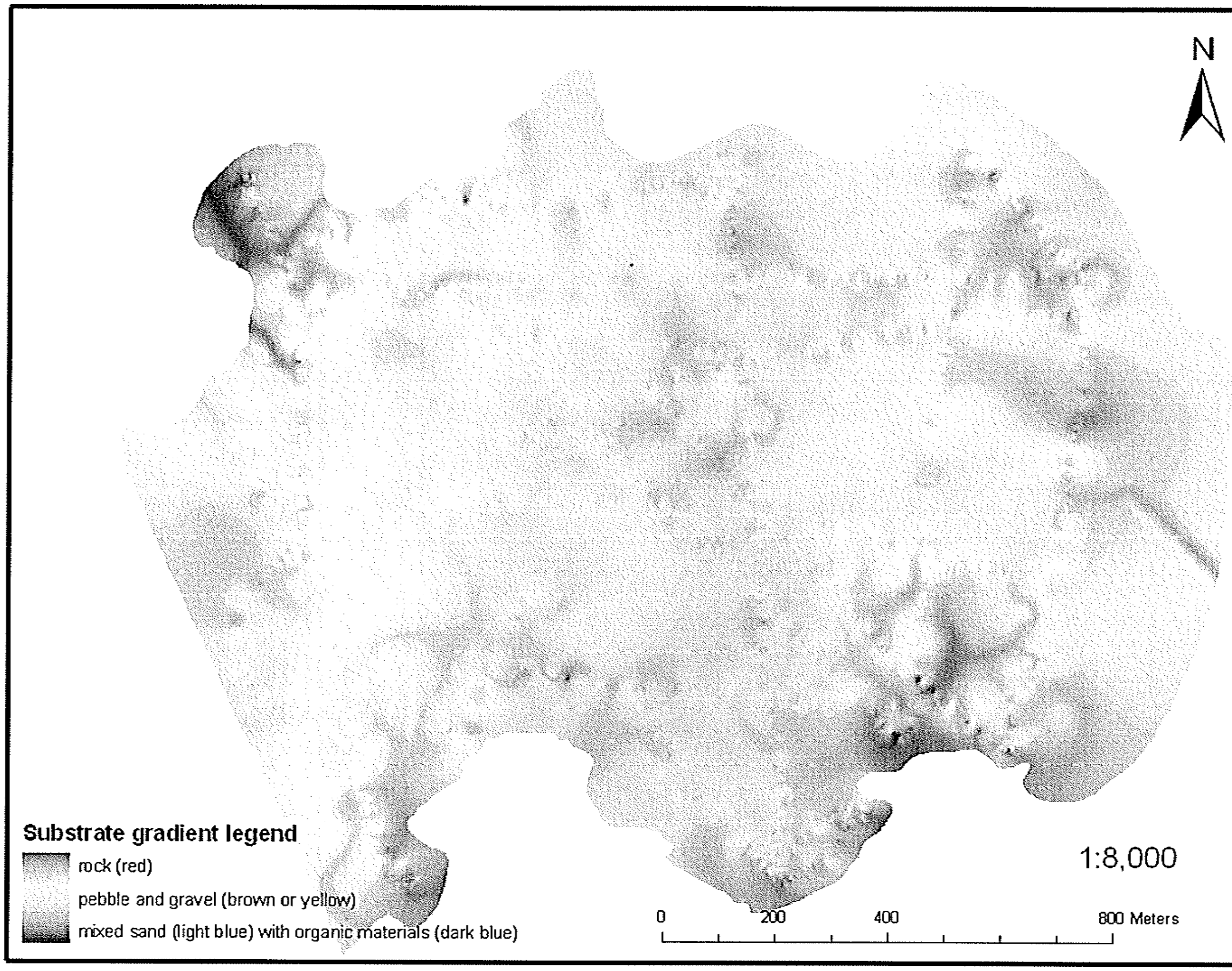

N
Substrate gradient legend
rock (red)
pebble and gravel (brown or yellow)
mixed sand (light blue) with organic materials (dark blue)
1:8,000
0
200
400
800 Meters

Figure 33. Substrate map of Seven Sisters, the Winnipeg River
The four substrates are rock, pebble/gravel, silt and silt with organic material. Most of the rock is located close to the dam of a power station. The pebble/gravel appears along the major flow from turbine and spillway. The silt and silt with the organic materials occurs in areas of low flow or no flow.

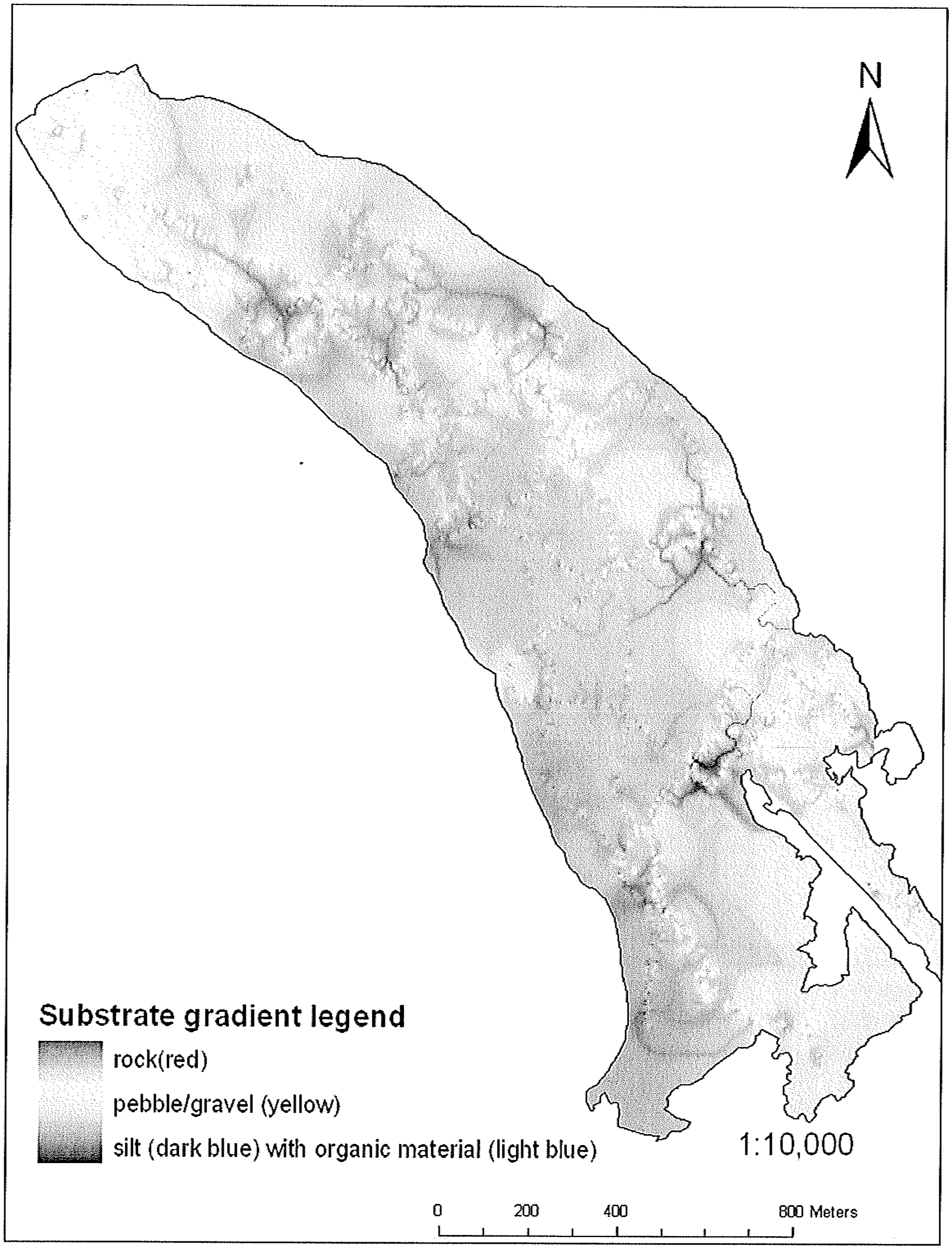

N
Substrate gradient legend
rock(red)
pebble/gravel (yellow)
silt (dark blue) with organic material (light blue)
1:10,000
0
200
400
800 Meters

Figure 34. Substrate map of Horseshoe Bend, the Mackenzie River
Two major substrate classes occur in the section of the river. The hard substrate consists of mixed sand and pebble/grave in the deep areas, and the soft substrate is comprised of silt/fine sand with organic materials.

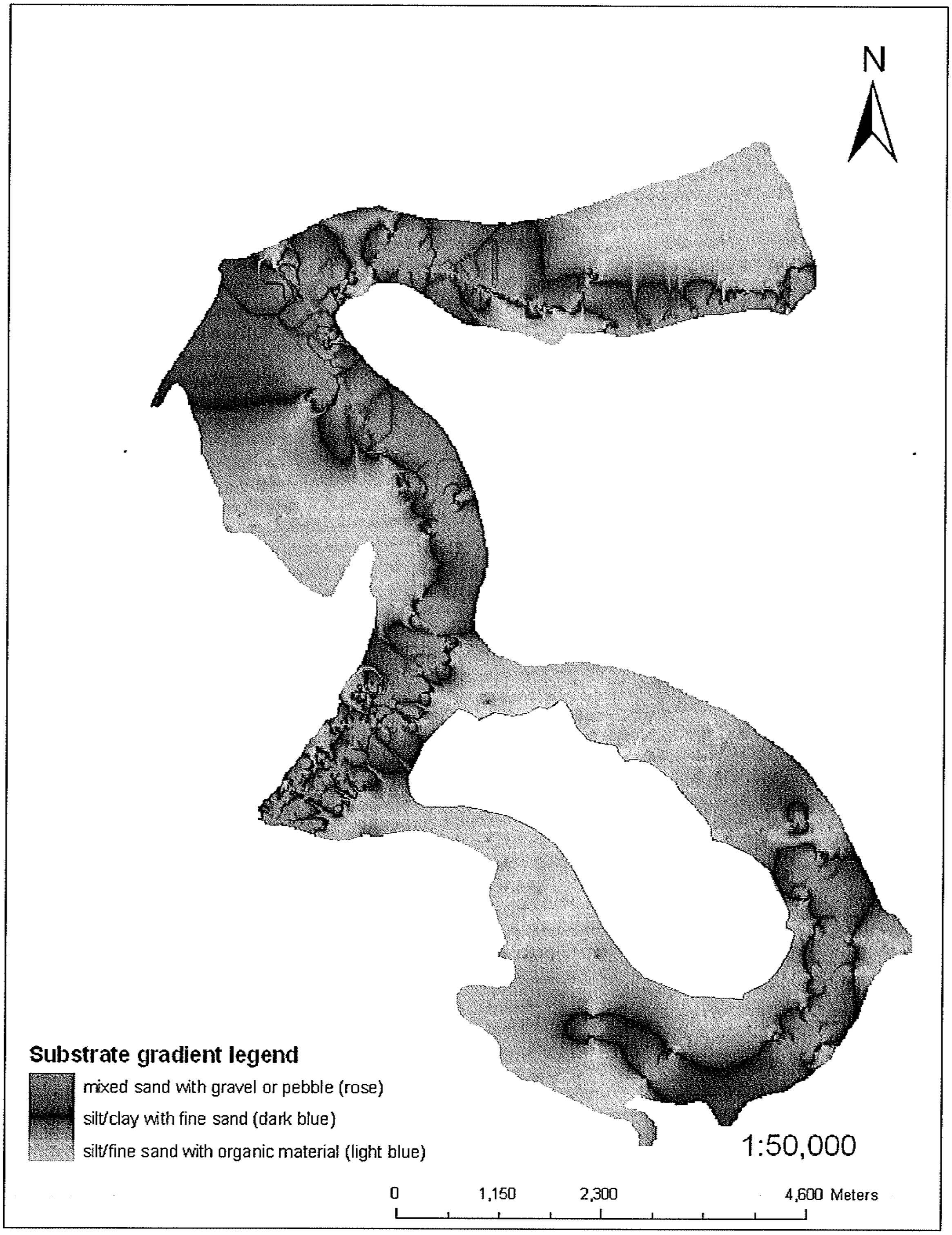

N
Substrate gradient legend
mixed sand with gravel or pebble (rose)
silt/clay with fine sand (dark blue)
silt/fine sand with organic material (light blue)
1:50,000
0
1,150
2,300
4,600 Meters

Figure 35. Substrate map of Chitty Lake
The majority of the lake bed is clumped organic material. Rock/boulder and pebble/gravel are distributed in the shallow areas around the bank, adjacent to areas comprised of pebble/gravel or vegetation. Pure clumped organic material is located at the center of the lake.

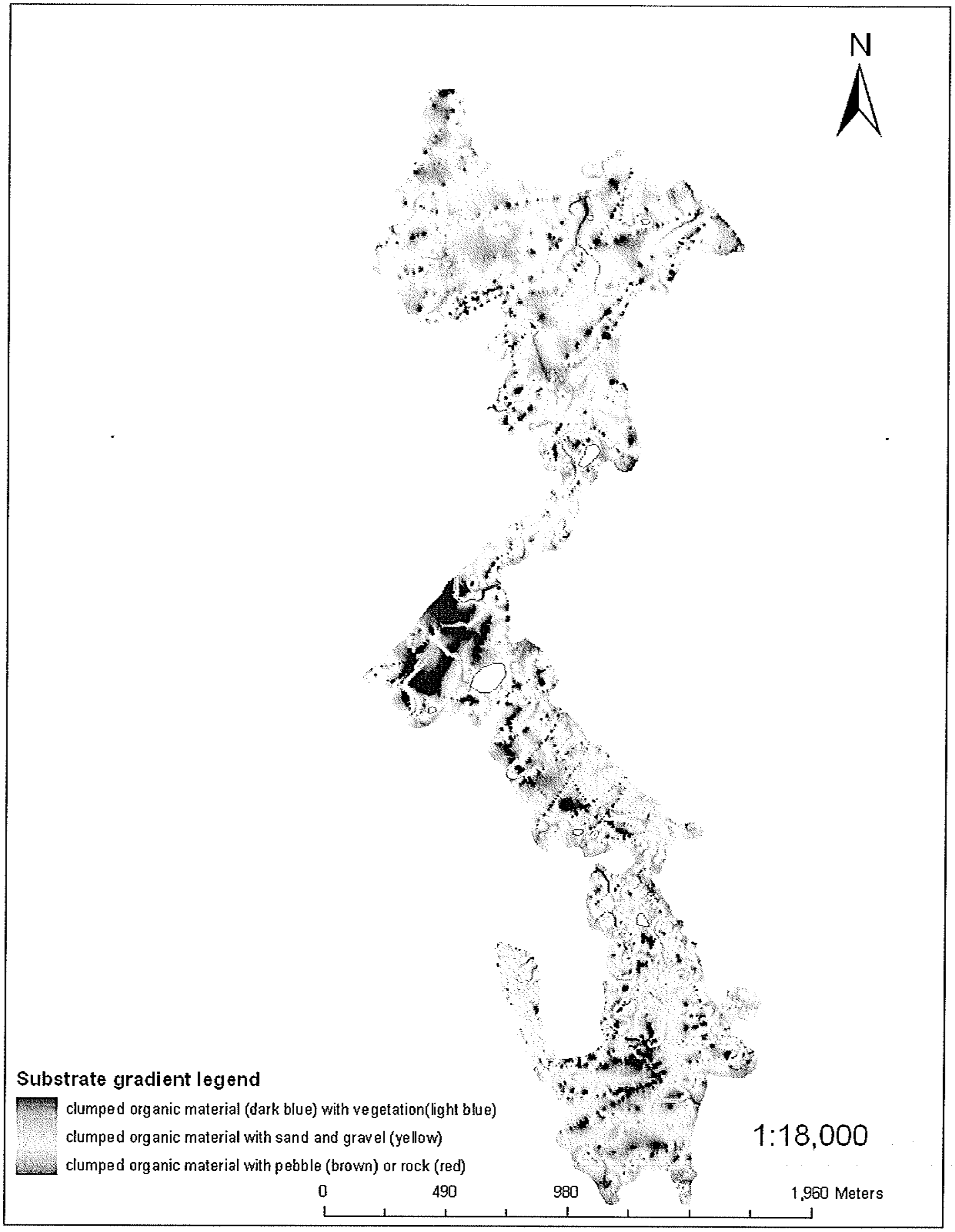
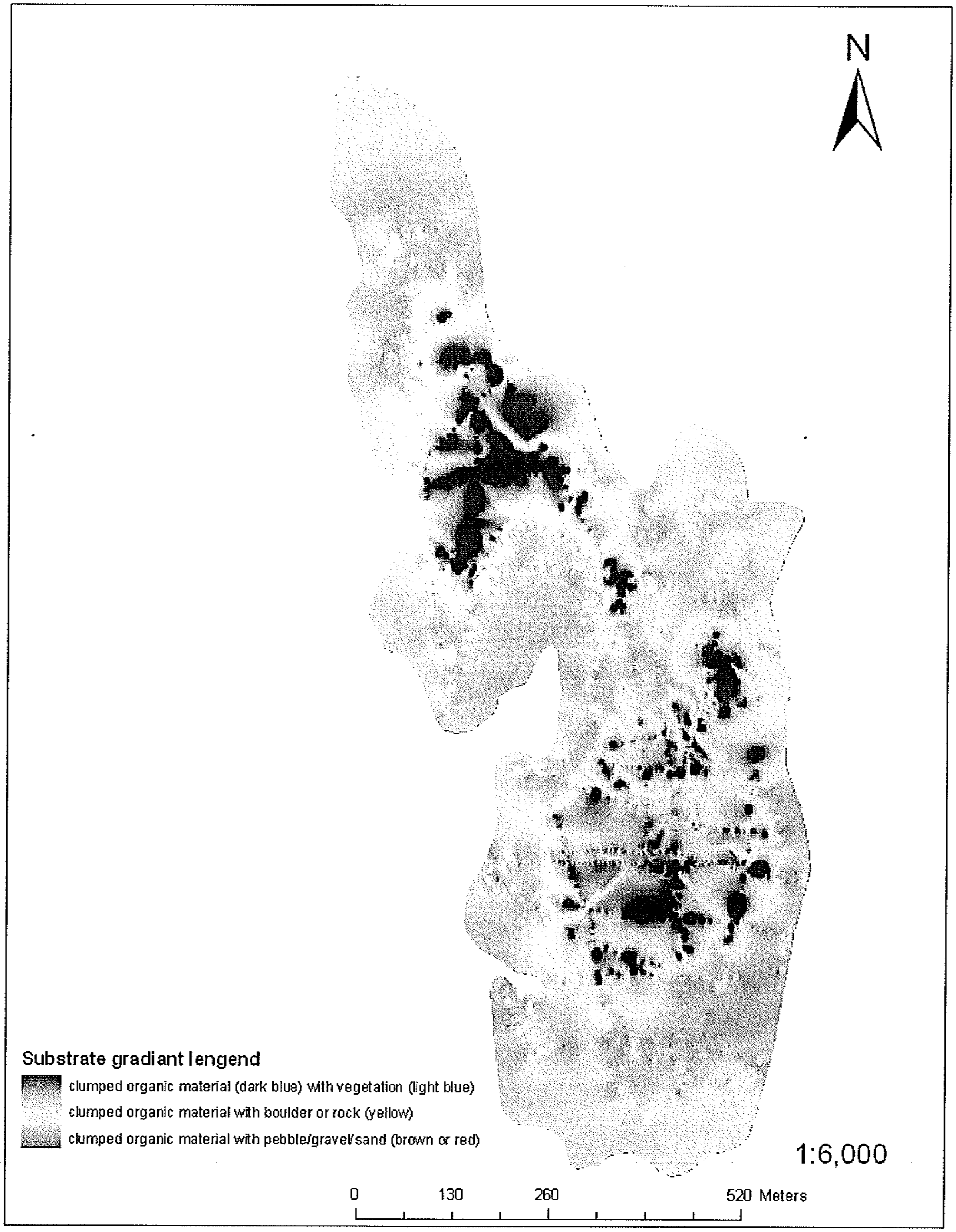

N
Substrate gradient legend
clumped organic material (dark blue) with vegetation(light blue)
clumped organic material with sand and gravel (yellow)
clumped organic material with pebble (brown) or rock (red)
1:18,000
0
490
980
1,960 Meters

Figure 36. Substrate map of Wormy Lake

The majority of the lake bed is clumped organic material. Rock/boulder and pebble/gravel are distributed in the shallow areas around the bank, areas adjacent to pebble/gravel are comprised of vegetation. Pure clumped organic material is located at the center of the lake.


N
Substrate gradiant lengend
clumped organic material (dark blue) with vegetation (light blue)
clumped organic material with boulder or rock (yellow)
clumped organic material with pebble/gravel/sand (brown or red)
1:6,000
0
130
260
520 Meters

Fish movement patterns and core ranges

All fish track data were acquired from the VEMCO VR2 receivers. The fish were implanted with 180 day and 2 or 3 year coded transmitters. Fifty six lake sturgeons (weight 944 to 24449 g and fork length 490 to 1273 mm) and thirteen Arctic chars (weight 95 to 2200 g and fork length 210 to 625 mm) were tagged and released respectively at Seven Sisters and at Wormy Lake in July while 16 lake trout (weight 1100 to 3100 g) and fork length 476 to 641 mm) were tagged at Chitty Lake in September.

Lake sturgeon

Seasonal movement

The lake sturgeon data in the area of Seven Sisters, Winnipeg River was collected for a period of 613 days (July 28th 2004 to November 23rd 2005). The receivers were removed during the winter due to the unstable ice conditions. The data from three lake sturgeons ranging in weight from 3372 g to 24449 g are presented here and were found to have higher and more extensive frequency of occurrence from July 28 to September 7, 2004 (Figure 37) than for the period from September 8 to October 28 (Figure 38). The less frequently used area during the latter period was close to the spillway. During the period from April 18 to June 5, 2005 (Figure 39), lake sturgeon became more active and their movement during this period was along the west shoreline, away from the central sector of the river. Lake sturgeon (Tag 205) has not been detected since the summer of 2005 (Figure 40). Although the distances and direction travelled by the lake sturgeons (Tag118 and Tag124) varied, they had similar patterns for the summer and fall of 2005 (From July 1 to November 23) (Figure 41, 42).

Core area of movement

A core area is defined in terms of the relatively high detection density. It was a smaller area with 40-60 percent of the total detections in any given period of time. A core area and non-core area of movement of lake sturgeon could be differentiated using a spatial analysis tool in GIS (named as kernel density in the ArcGIS 9.0). For example, lake sturgeon (Tag 124) had 128297 detections during the period from July 26 to August 23 2004. A core area was created on the detections using the kernel density and the area was 20% of the total detections. The number of detections within this area was 65098 (51% of 128297) (Figure 43).

Figure 37. Movements of three tagged lake sturgeons at Seven Sisters, the Winnipeg River

A total of 38714 detections were acquired for Tag118 (3372 g), 128297 detections for Tag124 (5789 g) and 43391 detections for Tag205 (24449 g) for the period from July 28 to September 7, 2004.

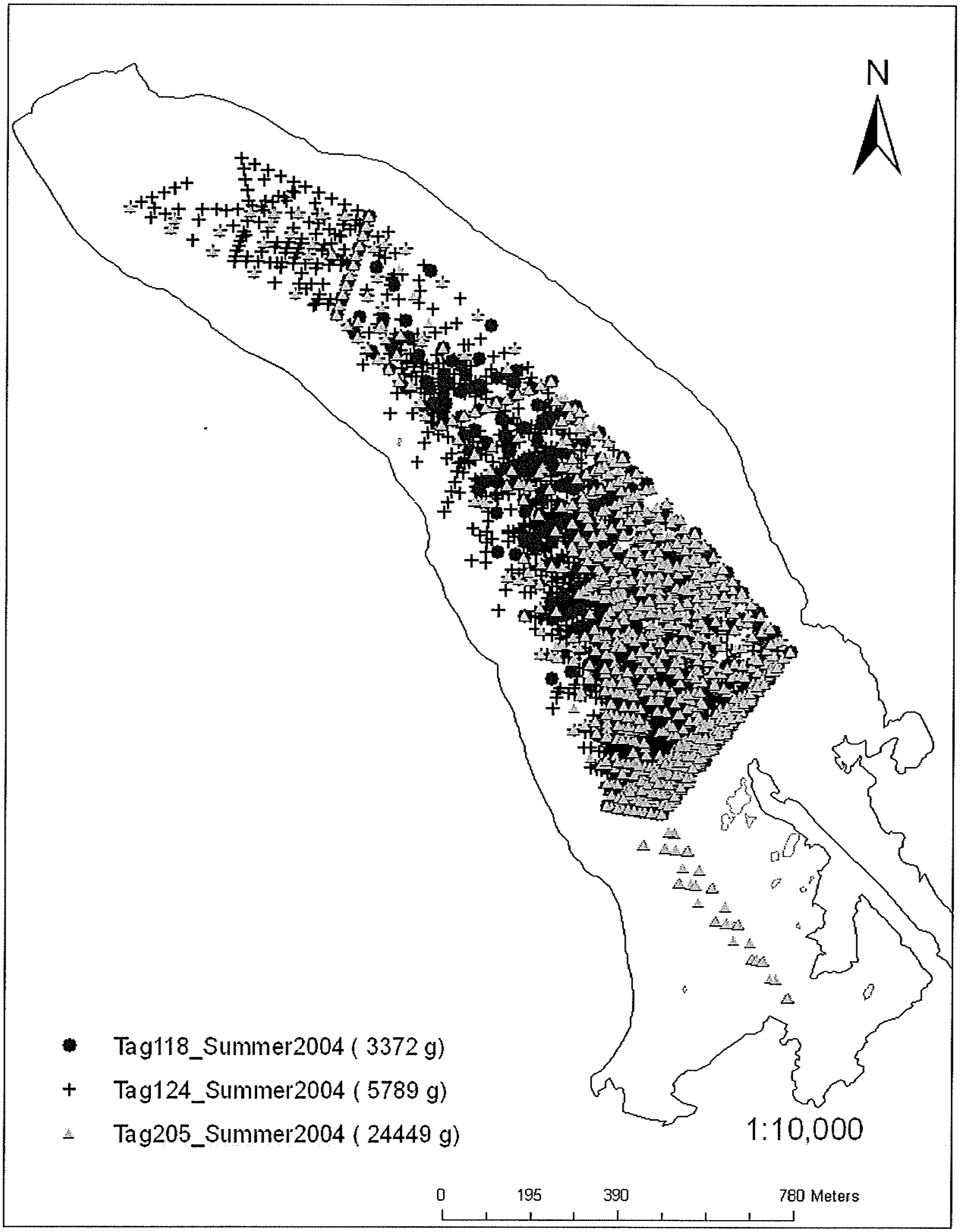

N
Tag118_Summer2004 (3372 g)
Tag124_Summer2004 (5789 g)
Tag205_Summer2004 (24449 g)
1:10,000
0
195
390
780 Meters

Figure 38. Movements of three tagged lake sturgeons at Seven Sisters, the Winnipeg River
A total of 7342 detections were acquired for Tag118 (3372 g), 46335 detections for Tag124 (5789 g) and 8649 detections for Tag205 (24449 g) for the period from September 7 to October 28 2004.

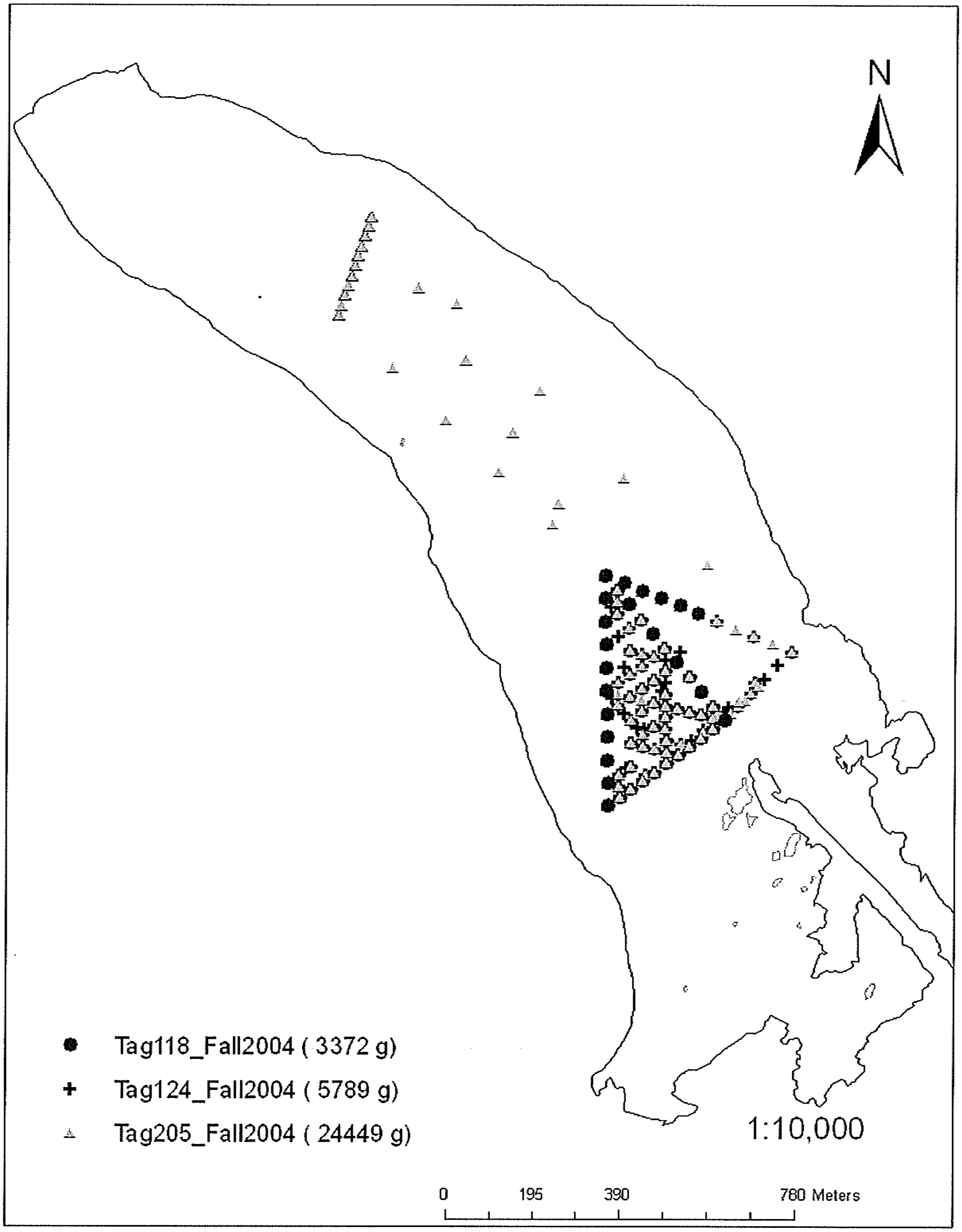

N
Tag118_Fall2004 (3372 g)
Tag124_Fall2004 (5789 g)
Tag205_Fall2004 (24449 g)
1:10,000
0
195
390
780 Meters

Figure 39. Movements of three tagged lake sturgeons at Seven Sisters, the Winnipeg River
A total of 31570 detections were acquired for Tag118 (3372 g), 18043 detections for Tag124 (5789 g) and 42049 detections for Tag205 (24449 g) for the period from April 16 to June 5 2005.

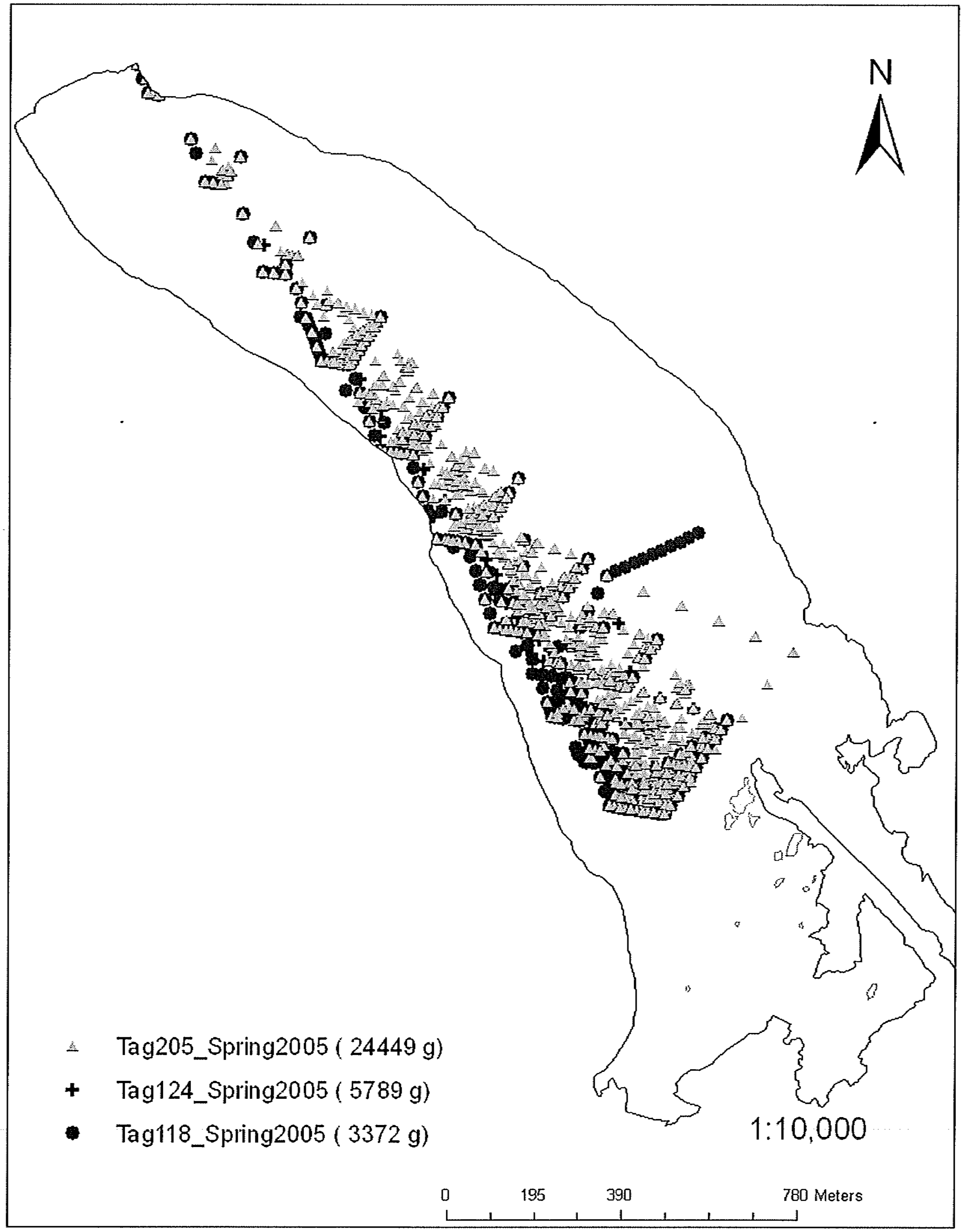

N
Tag205_Spring2005 (24449 g)
Tag124_Spring2005 (5789 g)
Tag118_Spring2005 (3372 g)
1:10,000
0 195 390 780 Meters

Figure 40. Movements of two tagged lake sturgeons at Seven Sisters, the Winnipeg River
A total of 16965 detections were acquired for Tag118 (3372 g) and 5707 detections for Tag124 (5789 g) for the period from July 1 to September 19 2005.

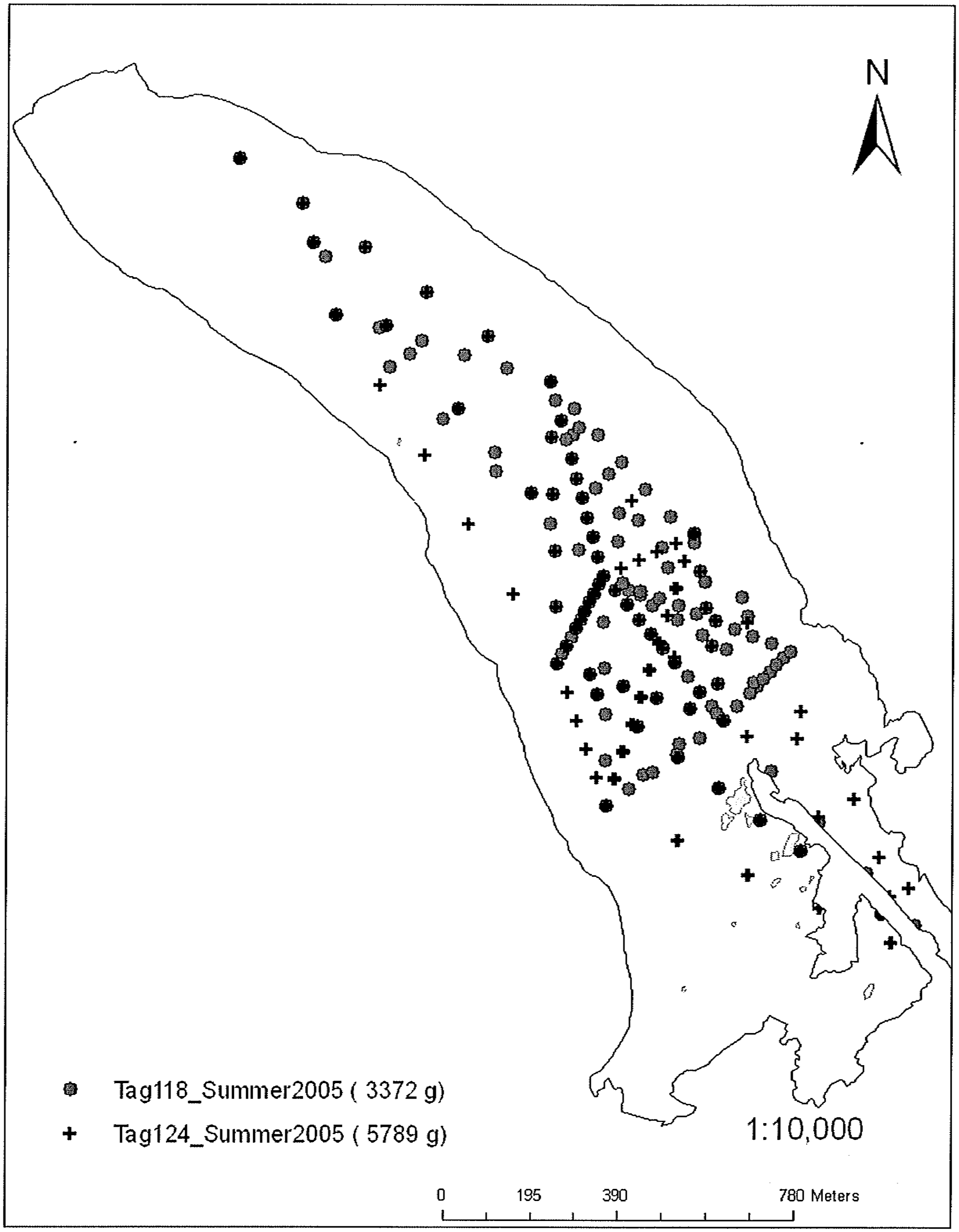

N
Tag118_Summer2005 (3372 g)
Tag124_Summer2005 (5789 g)
1:10,000
0
195
390
780 Meters

Figure 41. Movements of two tagged lake sturgeons at Seven Sisters, the Winnipeg River
A total of 8931 detections were acquired for Tag118 (3372 g) and 6302 detections for Tag124 (5789 g) for the period from September 19 to November 23 2005.

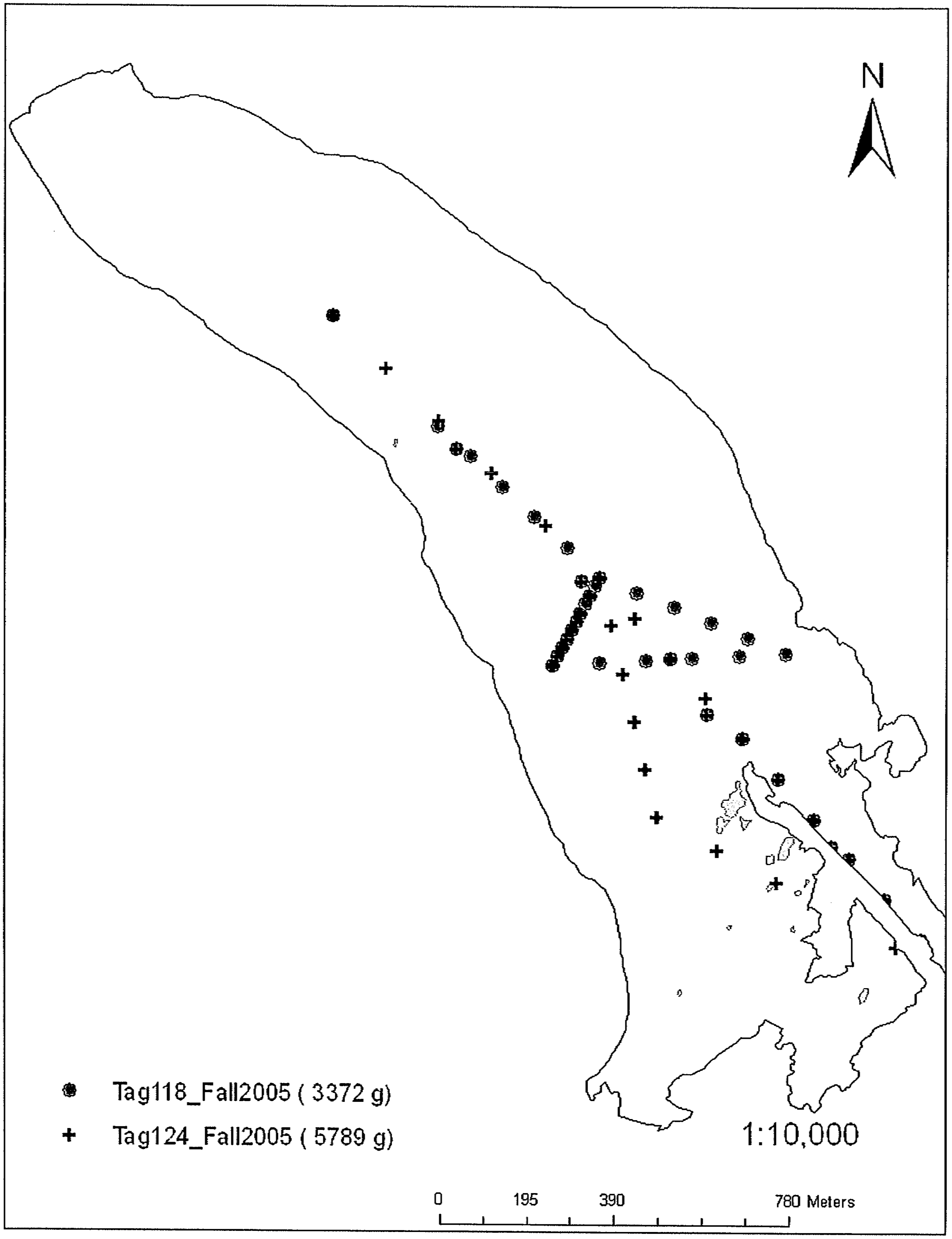
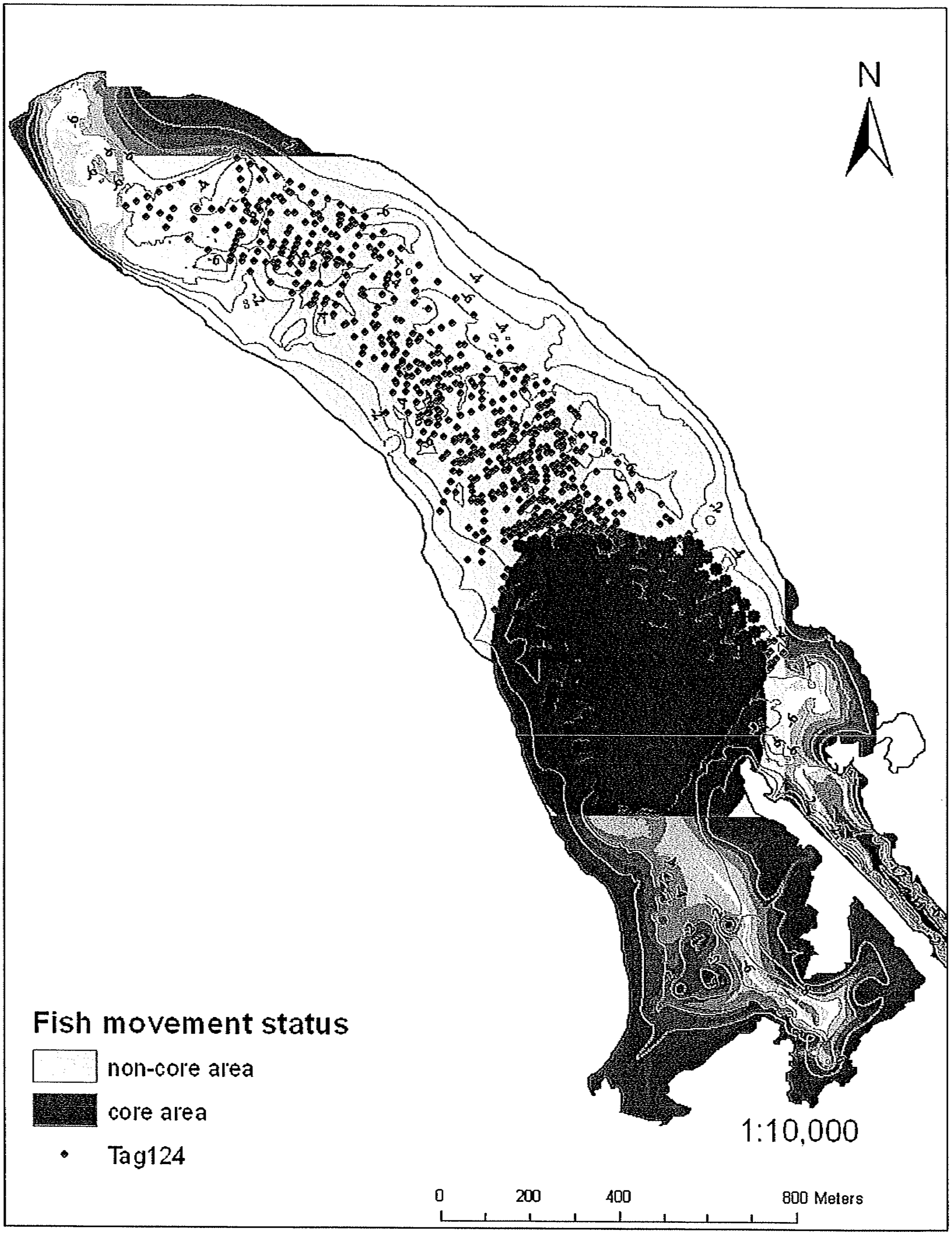

N
Tag118_Fall2005 (3372 g)
Tag124_Fall2005 (5789 g)
1:10,000
0
195
390
780 Meters

Figure 42. The core area of a lake sturgeon (Tag124, 5789 g) is built by the kernel density and overlapped with the high frequency of occurrence (51% of total detections).


N
Fish movement status
non-core area
core area
Tag124
1:10,000
0
200
400
800 Meters

Factors affecting movement

Based on an available bathymetric map of Seven Sisters (Figure 14, P80), the movement frequency of four lake sturgeons (Tag124, Tag178, Tag200 and Tag205) from July 26 to October 28 2004 by depth indicated preferred depths of 3 – 4 m, 2 – 3 m and 4 – 5 m respectively in the order of the detections. The less frequently used areas were 1 – 2 m and 5 – 6 m. No fish were found at 0 – 1 m and 8 m (Figure 43).

Also based on an available substrate map of Seven Sisters (Figure 33, P129), the lake sturgeon substrate preferences in terms of the frequency of occurrence over the substrates in order of importance were sand and organic sand mixture while the movements over gravel and pebble was less frequent. The least used substrates were silt and bedrock (Figure 44).

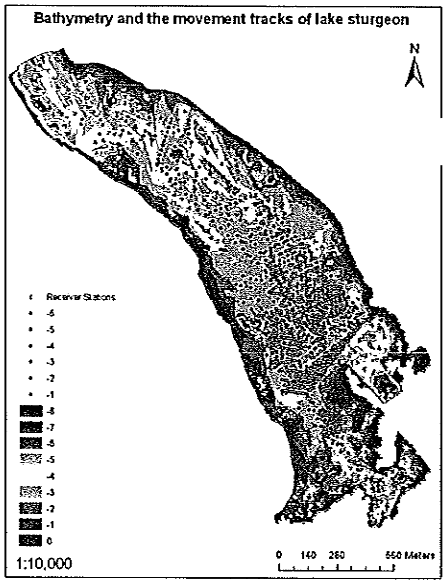
Water flow is fundamentally regulated by turbines and a spillway and ranged from 690 to 1823 cms during the period from July 26 to October 28, 2004 (Figure 45). The river flow was actually the same as the turbine flow when the spillway flow was 0 cms, but the turbine flow was more fluctuated for the period from August 7 to September 16, 2004 (Figure 45). Interestingly, the movement of a lake sturgeon (Tag 124) was correlated with the varying river flows during this period of this time. For example, the fish appeared 31times from 8/21/2004 0:00 to 8/21/2004 0:59 and the hourly water flow was 869 cms, 115 times from 8/21/2004 1:00 to 8/21/2004 1:59 and the hourly water flow was 886 cms, …, 157 times from 8/21/2004 23:00 to 8/21/2004 23:59 and the hourly water flow was 1004 cms. A total of 1015 times occurred and 24 varying water flows (869 cms to 1007 cms) were available on 8/21/2004. More than half of the total detections occurred when flows were between 690 cms and 1050 cms over 40 days (Figure 46) and were concentrated in about 30 percent of the area of the entire survey section (Figure 47).

Lake trout

Core area of movement

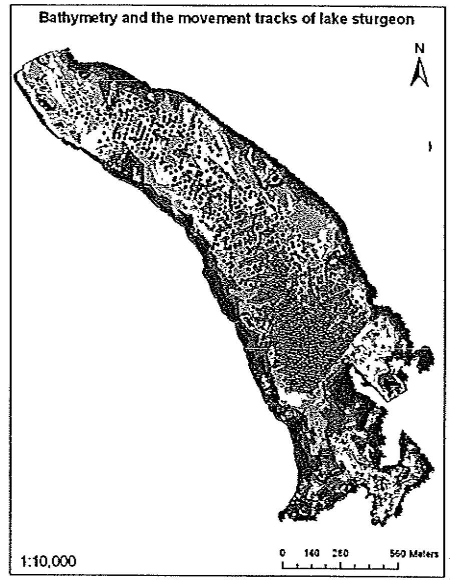
Site fidelity of lake trout can be differentiated on the map with the help of a simulation program. The simulation points have indicated that two populations exist in

Figure 43. Bathymetry and the movement of four lake sturgeons at Seven Sisters, the Winnipeg River A graph illustrates the movements of the four lake sturgeons over at each 1 m interval
A: Tag205; B: Tag124; C: a chart for four fish; D: Tag178; E: Tag200



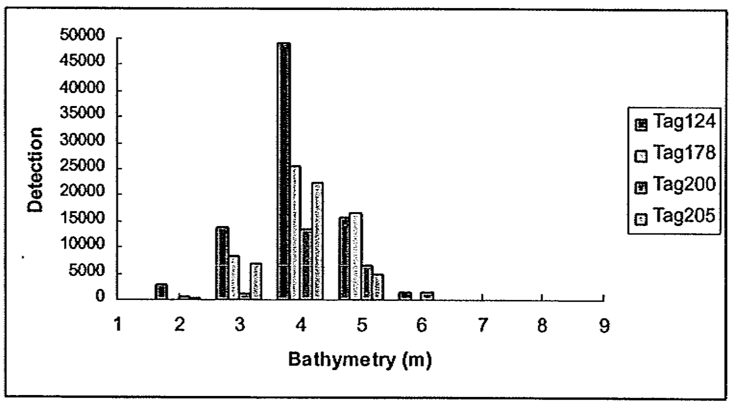
Bathymetry and the movement tracks of lake sturgeon
N
Receiver Stations
1:10,000
0 140 280 560 Meters

A



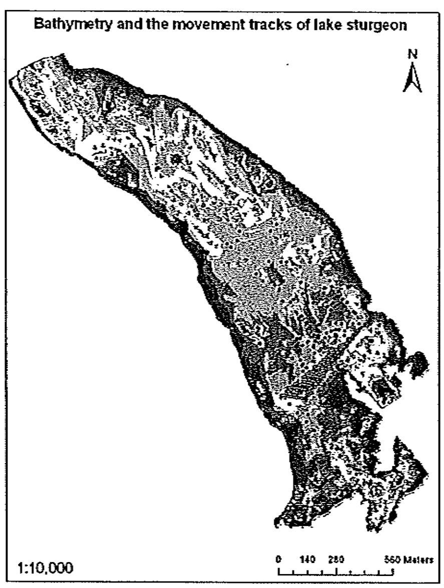
Bathymetry and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters

B



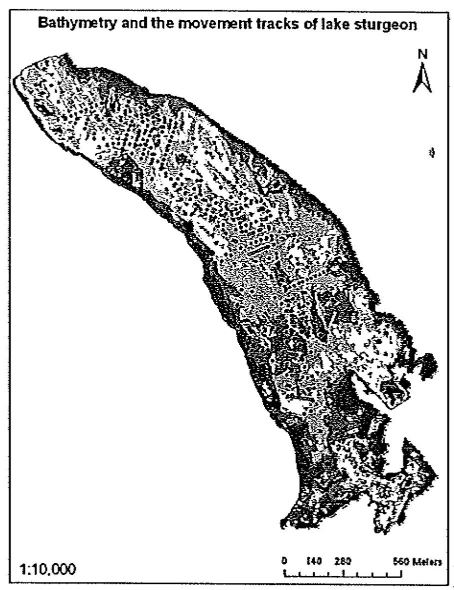
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Detection
1
2
3
4
5
6
7
8
9
Bathymetry (m)
Tag124
Tag178
Tag200
Tag205

C



Bathymetry and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters

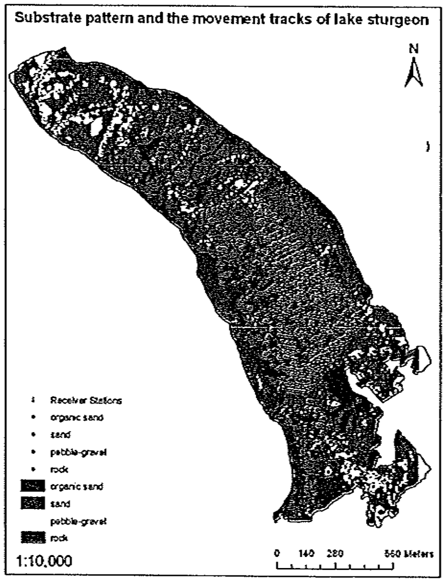
D

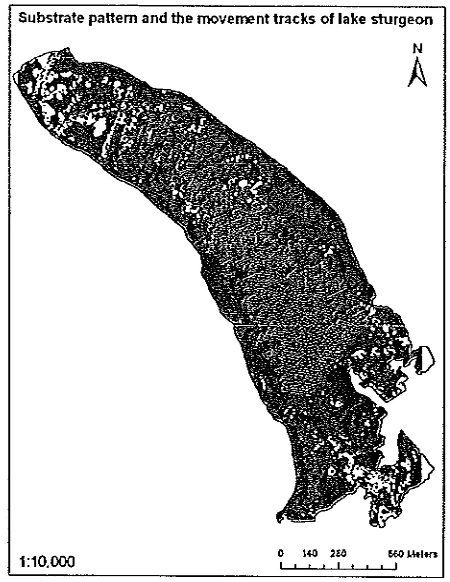


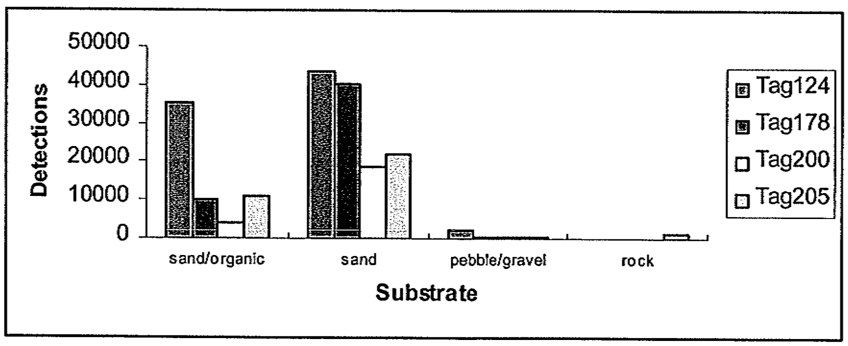
Bathymetry and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters

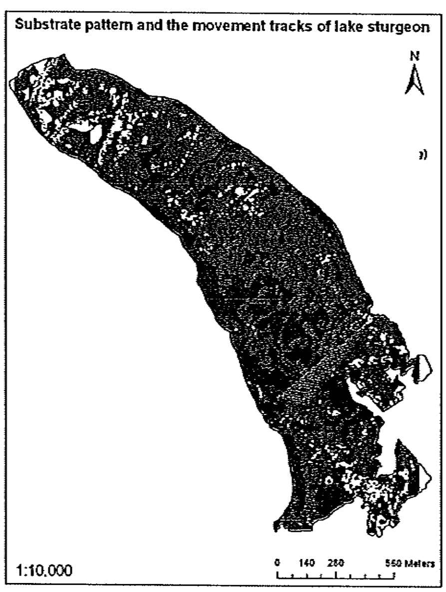
E

Figure 44. Substrate pattern and the movement of four lake sturgeon in the Winnipeg River below Seven Sisters
A graph illustrates the movements of four lake sturgeons over the substrate types.
A: Tag205; B: Tag124; C: a chart for four fish; D: Tag178; E: Tag200


Substrate pattern and the movement tracks of lake sturgeon
N
Receiver Stations
organic sand
sand
pebble-gravel
rock
organic sand
sand
pebble-gravel
rock
1:10,000
0 140 280 560 Meters


Substrate pattern and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters


50000
40000
30000
20000
10000
0
Detections
sand/organic
sand
pebble/gravel
rock
Substrate
Tag124
Tag178
Tag200
Tag205


Substrate pattern and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters

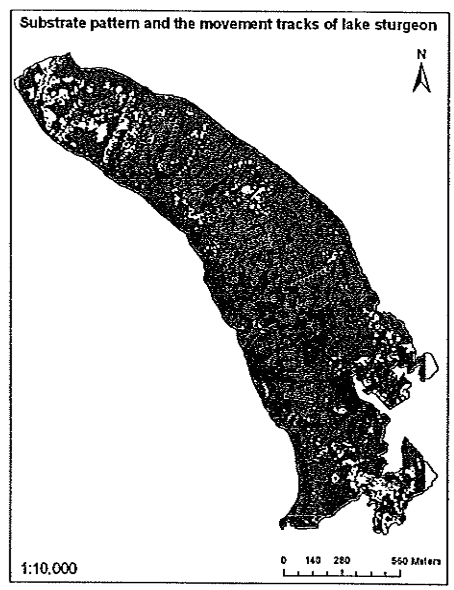

Substrate pattern and the movement tracks of lake sturgeon
N
1:10,000
0 140 280 560 Meters

Figure 45. Illustration of the turbine flow and the spillway flow from July 26 to October 26, 2004 at Seven Sisters, the Winnipeg River
Rectangle: August 7 to September 16, 2004.

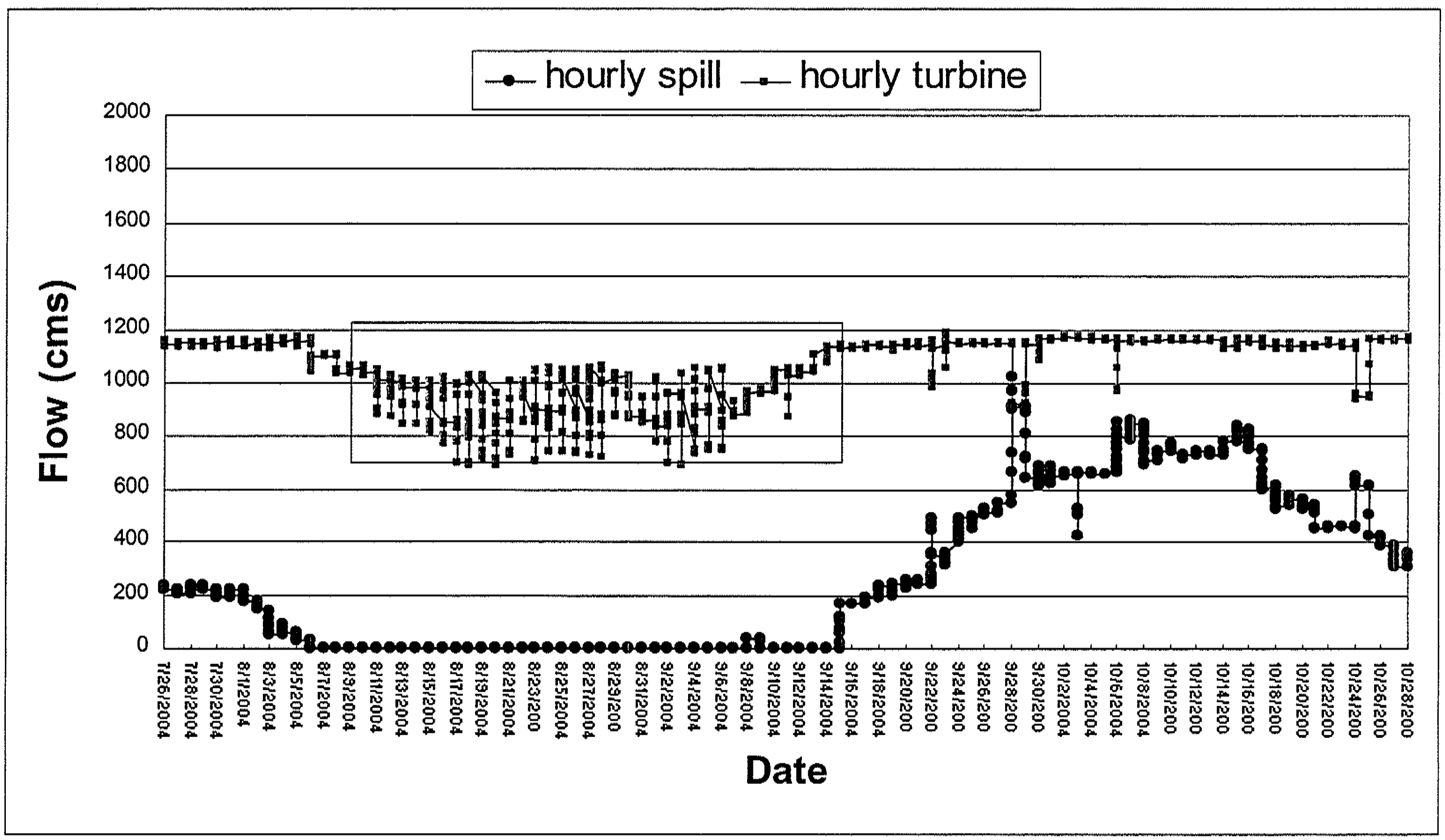
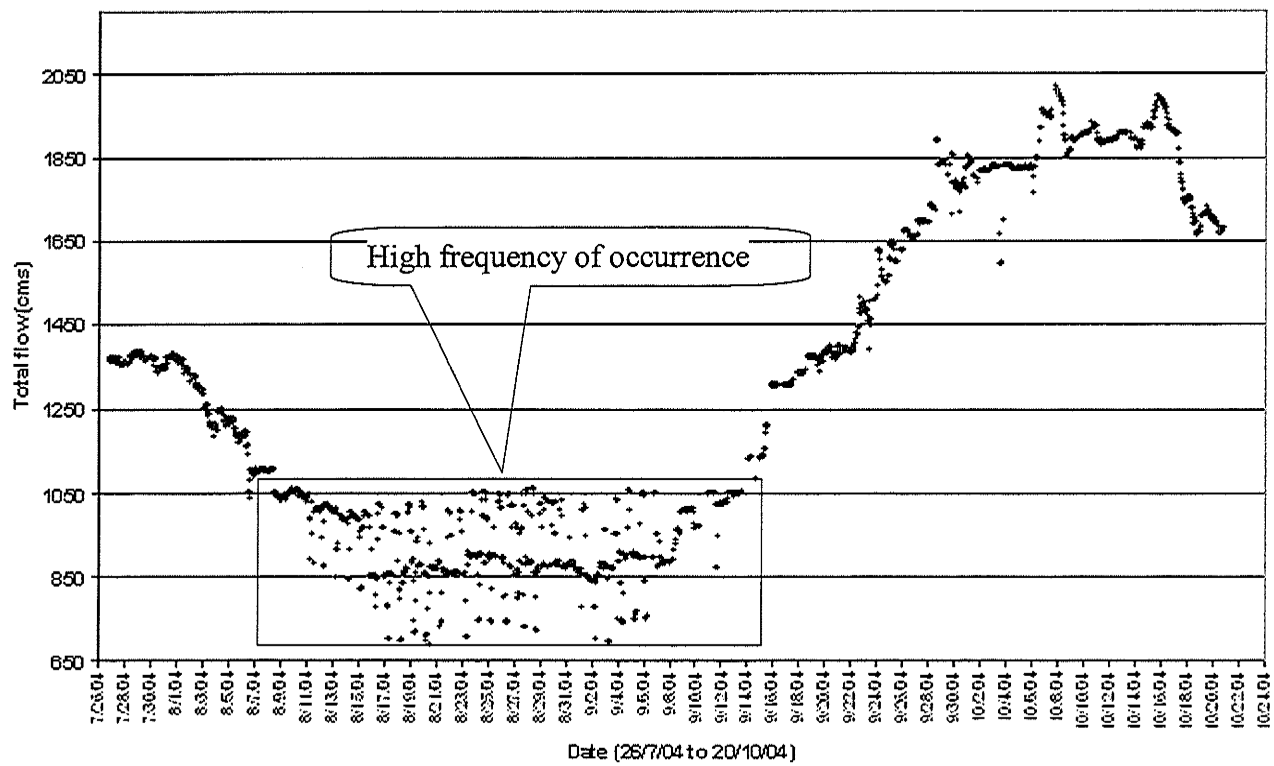
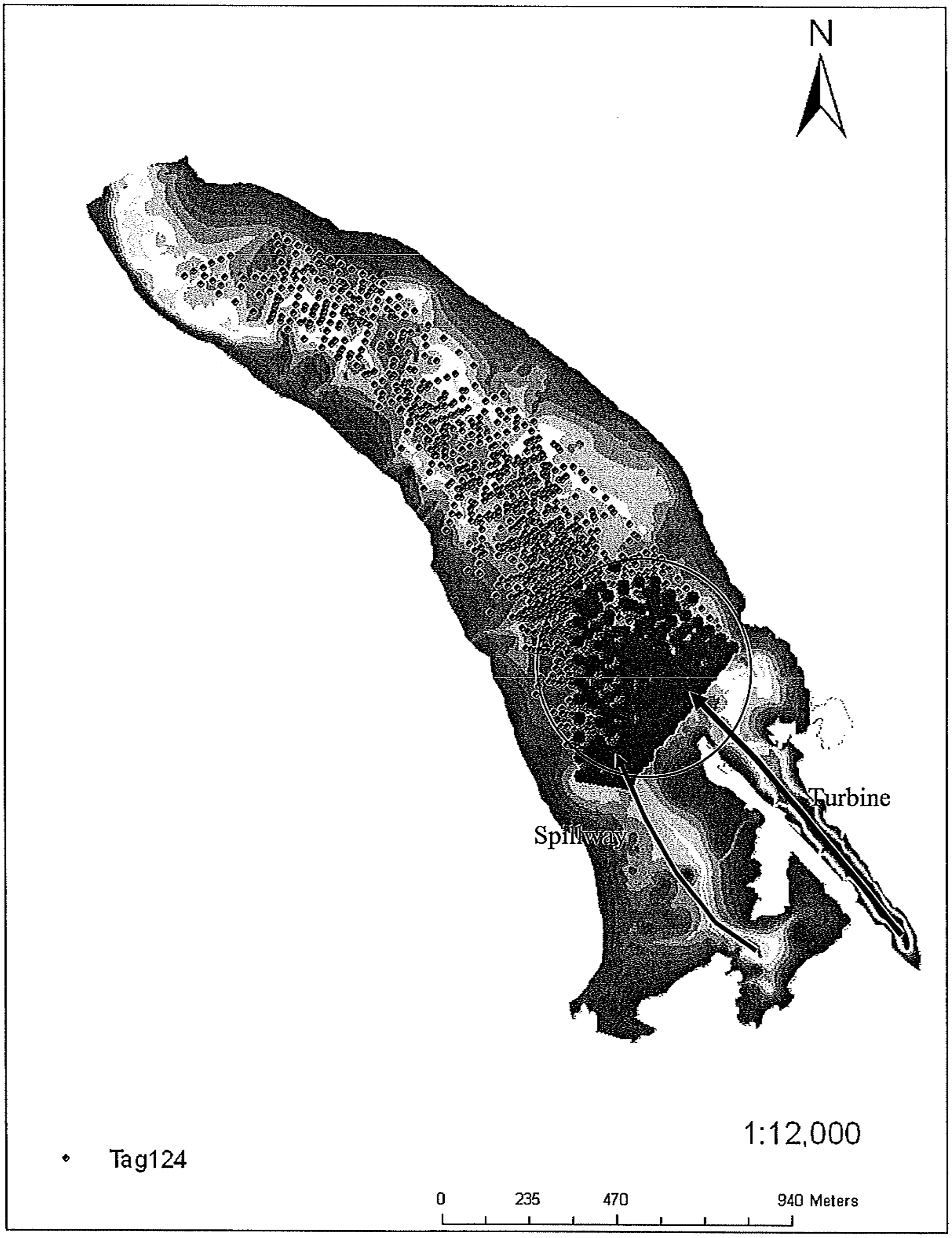

hourly spill
hourly turbine
Flow (cms)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Date
7/26/2004
7/28/2004
7/30/2004
8/1/2004
8/3/2004
8/5/2004
8/7/2004
8/9/2004
8/11/2004
8/13/2004
8/15/2004
8/17/2004
8/19/2004
8/21/2004
8/23/200
8/25/2004
8/27/2004
8/29/200
8/31/2004
9/2/2004
9/4/2004
9/6/2004
9/8/2004
9/10/2004
9/12/2004
9/14/2004
9/16/2004
9/18/2004
9/20/200
9/22/200
9/24/200
9/26/200
9/28/200
9/30/200
10/2/2004
10/4/2004
10/6/2004
10/8/2004
10/10/200
10/12/200
10/14/200
10/16/200
10/18/200
10/20/200
10/22/200
10/24/200
10/26/200
10/28/200

Figure 46. Movement of lake sturgeon affected by water flow over time. Plot displays how many times a fish (Tag124) appeared as the hourly water flows varied each day. Note that the lake sturgeon was still detected at the high flows of 1050-1300 cms, but the variation was less.
Rectangle: August 7 to September 16, 2004.



High frequency of occurrence
Total flow(cms)
2050
1850
1650
1450
1250
1050
850
650
Date (26/7/04 to 20/10/04)

Figure 47. Location of lake sturgeon during varied water flows
Lake sturgeon (Tag124) appeared as the hourly water flows varied each day. Note the frequency of occurrence of the lake sturgeon movements and the water flows of the total from both the turbine and the spillway (two arrows). Points are in the area of the river during the period from July26 to October 28 2004. Circle refers to the core area.


N
Turbine
Spillway
1:12,000
Tag124
0
235
470
940 Meters

Chitty Lake because the trout from the north and south basin returned to the basin of capture. Consequently, there were two core areas in Chitty Lake depending on what basin a lake trout came from. A lake trout (Tag75) always remained in the south basin during the period September 17 to October 31, and its core area was located at the south basin (Figure 48)

Factors affecting movement

There were individual differences in the movements with respect to the depth and the temperature for lake trout. A post spawning lake trout (Tag75 / temperature, Tag76 / pressure) was found at 12-14 m as temperature decreased from 8 °C to 3 °C between September 18 and October 16. The temperature was at above 8 °C prior to September 18 and below 3 °C after October 16, and this fish preferred real depths of 4-8 m (Figure 49A). A male lake trout (Tag81 / temperature, Tag82 / pressure) frequented depths similar to the female trout until temperatures were below 3 °C, but remained in deep areas when the temperature was less than 3 °C after October 16 (Figure 49B).

<u>Arctic char</u>

Core area of movement

Arctic char occurred more in the south basin. The core area for the Arctic char covered bathymetric zones of 16-18 m (Figure 50).

Factors affecting movement

Arctic char (Tag 90) was found most often at the depths of 4-18 m, but occasionally moved into shallower regions of Wormy Lake (Figure 51). In general, the preferred depth for char ranged from 0–9 m with the majority of fish found at 6-9 m when the photoperiod was between 16.5 and 24 hours of light. The depth range expanded from 8 to 18 meters and was more variable during the period from July 20 to August 14 when the photoperiod decreased from 16.38 to 15.63 hour of light, but the depth range increased to 0–18 m as the photoperiod continued to decline (see two arrows in Figure 51).

Arctic char did not vary their movements for the period from July 15 to August 23, 2004 regardless of size, although large fish (1450-2200 g) were more active than medium and small ones (less than 700 g) (Figure 52). Note that it was a longer daytime

(21.55 hrs) and the Arctic char were probably insensitive to the shift from daytime to night time.

Figure 48. Lake trout core area
A core area of a lake trout (Tag75, 2550 g) is based on kernel density and overlapped with the high frequency of occurrence (78% of total detections).

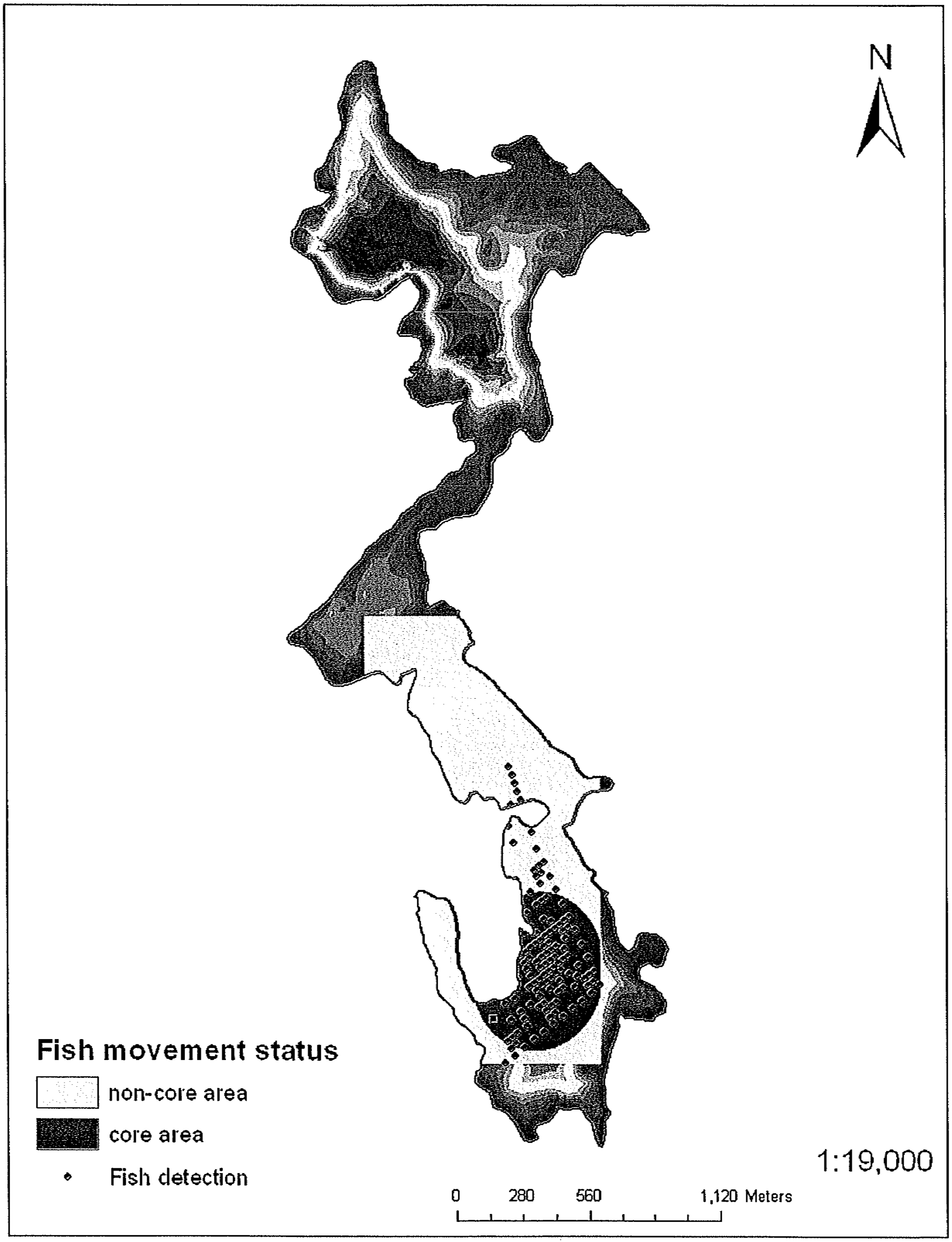
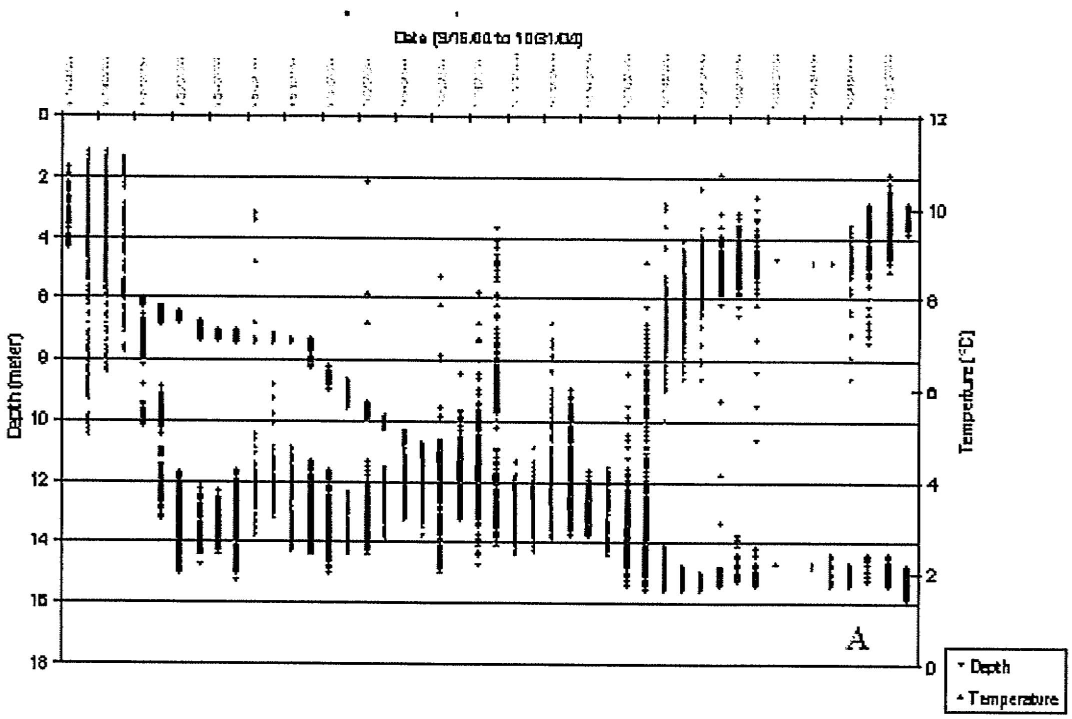
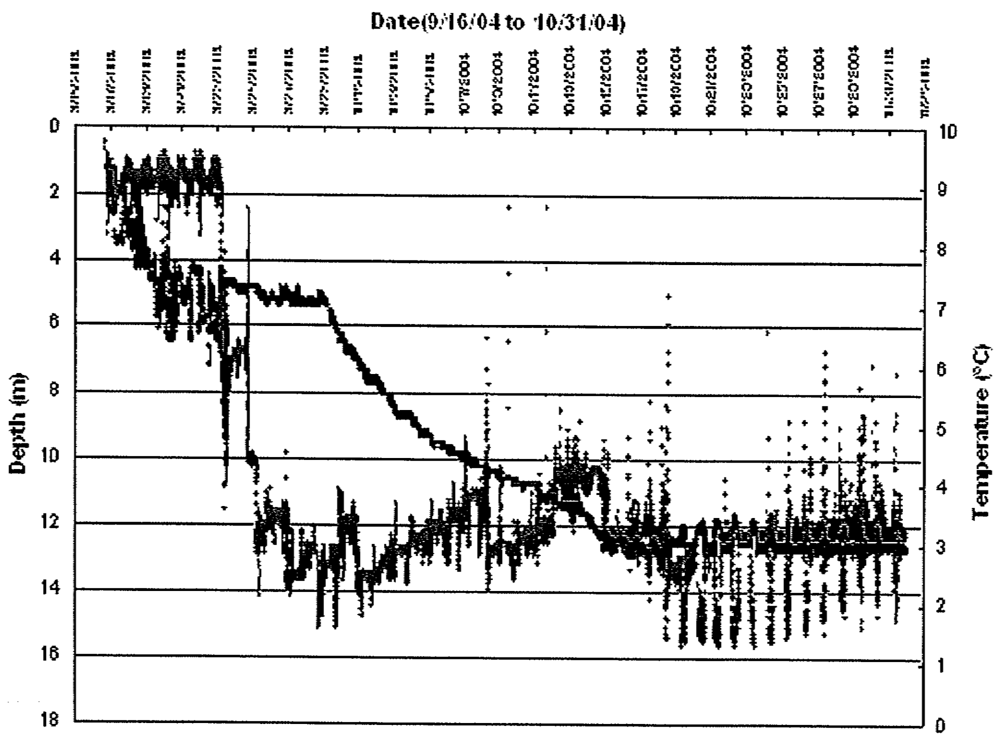

N
Fish movement status
non-core area
core area
Fish detection
1:19,000
0
280
560
1,120 Meters

Figure 49. The distribution of a male (Tag81, 82) and a female (Tag75, 76) lake trout with a tag containing depth and temperature sensors
A: Female
B: Male


Date (9/16/04 to 10/31/04)
Depth (meter)
Temperature (°C)
A
Depth
Temperature


Date(9/16/04 to 10/31/04)
Depth (m)
Temperature (°C)

B

Figure 50. Arctic char core area

A core area of an Arctic char (Tag90, 1850 g) based on kernel density and overlapped with the high frequency of occurrence (61% of total detections).

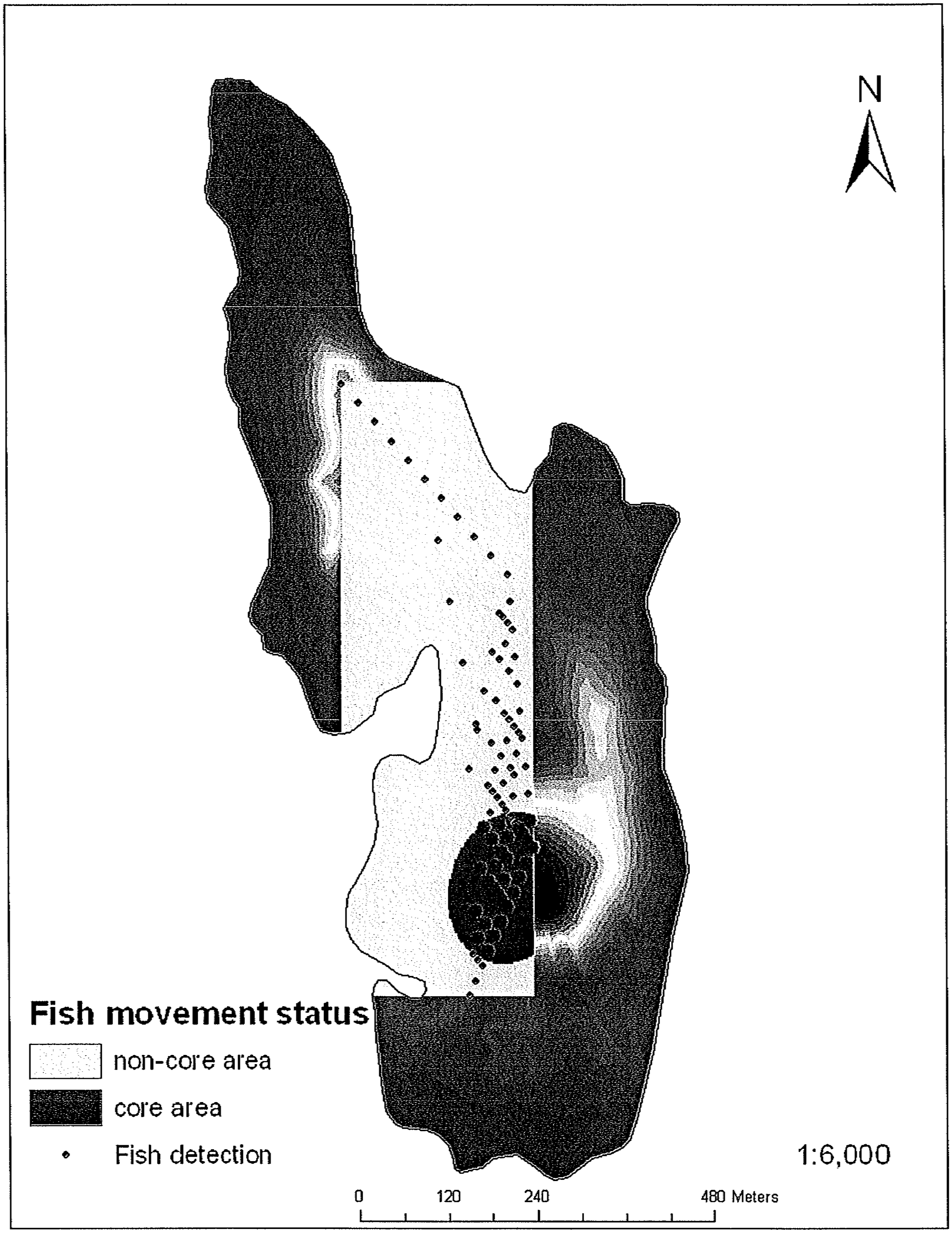

N
Fish movement status
non-core area
core area
Fish detection
1:6,000
0
120
240
480 Meters

Figure 51. Depth distribution of an Arctic char
This figure illustrates the range of depth selection by an Arctic char (Tag90, 1850 g). Arrows indicate: (1) sunrise time: sunset time = 3:29: 19:46; (2) sunrise time: sunset time = 3:47: 9:25.

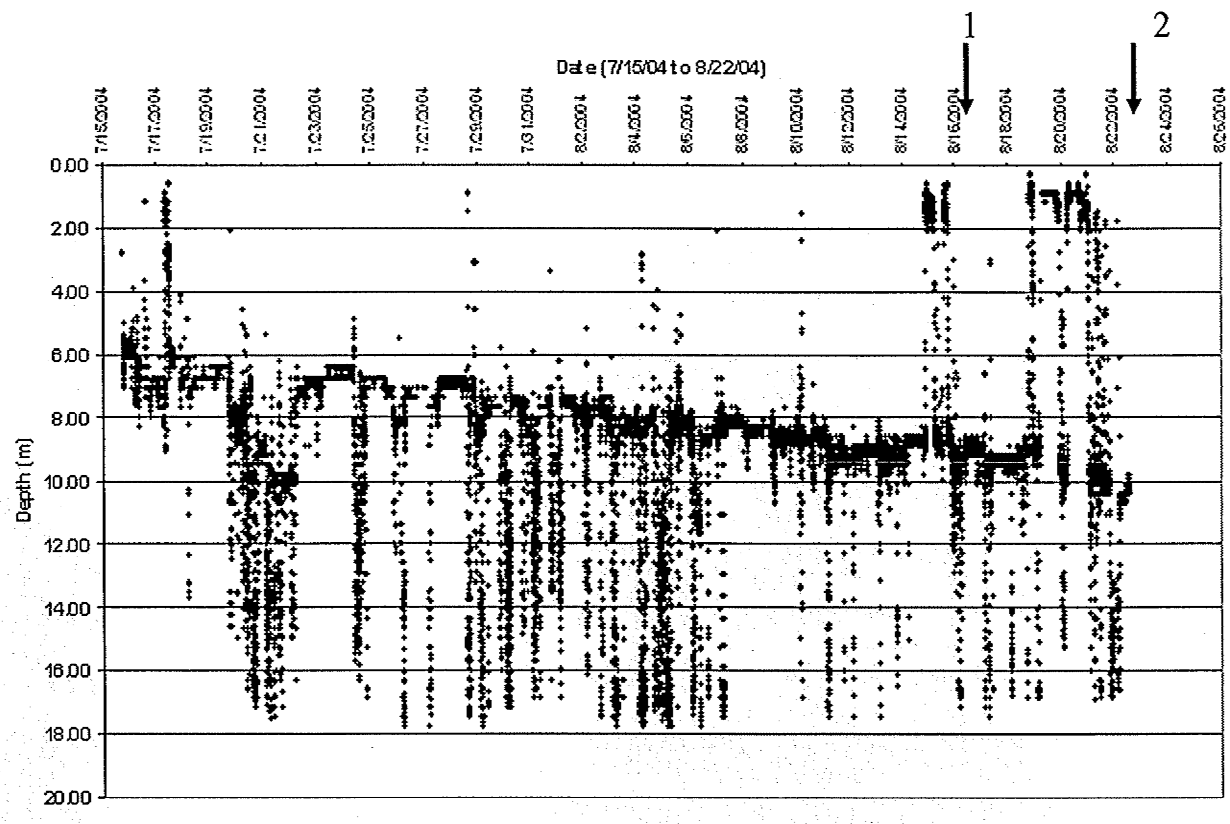
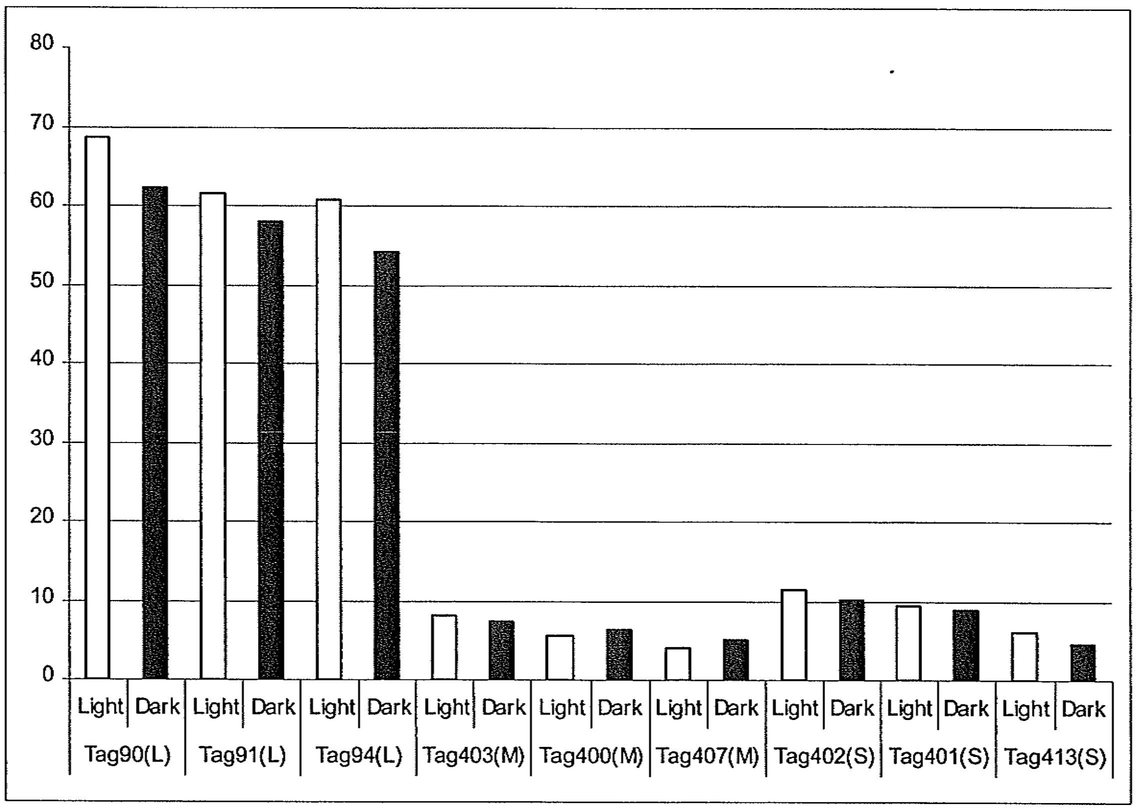

1
2
Date (7/15/04 to 8/22/04)
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00

Figure 52. Hourly detections of ten Artic char at Wormy Lake for 24 hours during July 15 to August 23 2004
Photoperiod: from17.5 hrs to 21.5hrs of daylight between July 15 and August 23, 2004
A: Light bar for daytime
B: Dark bar for night time



80
70
60
50
40
30
20
10
0
Light
Dark
Tag90(L)
Tag91(L)
Tag94(L)
Tag403(M)
Tag400(M)
Tag407(M)
Tag402(S)
Tag401(S)
Tag413(S)

CHAPTER 5 DISCUSSION

Interpolation methods for bathymetry

Topogrid was performed for all the bathymetry maps in this project. It was compared with the other interpolation tools such as the triangulated irregular networks (TIN) and the inverse distance weighting (IDW), and the Kriging at the same image resolution of 2 m. The available options included sampling weights, search distances, mathematical 'fit' functions which required the knowledge of statistics and the conditions of water bodies prior to a study. The rooted mean square error (RMSE) was used to indicate the numerical accuracy of the spatial analysis in GIS. The errors propagated by the interpolation methods such as TIN, IDW, Kriging and Topogrid were estimated using the RMSE and were calculated in terms of Equation 1:

$$RMSE = \sqrt{{SSE_i^2}/{n}} \quad \text{-----} (1)$$

where SSE is the sum of errors (observed - estimated values) and n is the number of pairs (errors). The interpolated values (estimated values) at the point locations (observed values) can be run automatically to avoid the manual bias by using the Extract Values to Point of Spatial Analysis Tools in the latest ArcGIS (version 9.0). The entire acoustic track records from Falcon Lake were selected to calculate the RMSE because it is a particularly complete data set with many benthic samples used for visual inspection. The results indicated the relatively high accuracy of the four interpolation methods used but the interpolation using TIN (0.13584641) yielded the smallest errors while the others were larger: TOPOGRID (0.199926993), IDW (0.21719246), Kriging (0.23514116). The TIN was more accurate than the other three grid based methods because the original acoustic data points were located on the surface (Hu, 1995). Siska and Huang (2001) came to a similar conclusion when TIN (9.92), IDW (15.10), Kriging (10.00), Trend (12.00) and Thienssen (43.00) were compared in the RMSE.

The ridges and the stream lines of TIN are helpful to describe the complex relief of the river/lakebed, but a large number of break lines and spikes can hinder the spatial analysis, such as the derivation of the contours. The triangular discretizations for TIN's interpolation and the jaggy contour lines for the TIN's derivation make the continuous surface of the aquatic bottom unnatural and dim in colours. This may be the reason why the interpolation method has not been widely applied to bathymetry, even though it gives the most accurate bathymetric maps. By contrast, an interpolated image using grid based methods has derived contour lines that are smooth, although the RMSE arising from them is a little bit larger than that from TIN.

The application of IDW (Carter and Shankar, 1997) and Kriging (Burroughes, 2001, Valavanis, et al., 2003) to the bathymetry was not a simple direct performance for accuracy because of a local domain (IDW). Kriging can illustrate more complicated features than IDW, but many of the pre-processing algorithms made interpolation very inconvenient. Hutchinson (1998) combined the useful parts of IDW, Kriging and Spline into a specific approach called Topogrid for hydrological DEM. This method takes into account ridges, stream lines, drainage and sink systems on the floor of a water body, but to date it is not widely used by aquatic researchers for bathymetry. Since Topogrid interpolation produced the best bathymetric prediction among the grid based methods and being only slightly less precise than TIN, and more importantly depicted the drainage systems well, it was the method of choice for the bathymetric interpolation in this thesis.

Minimization of spatial uncertainty for acoustic verification

To date, no universal approach to substrate mapping has been developed. The various approaches have advantages and disadvantages when applied to the acquisition and processing of the substrate data (see "Literature Review"). One needs to combine at least two approaches to obtain quality data, 1) acoustic technologies (mainly AGDC) were used as remote methods to accurately discriminate the sea/river/lake bed in substrates and 2) ground-truth tools (mainly benthic samplers) were combined to identify the physical substrate features directly in the sparsely sampled sites. Regardless of the error sources from the acoustic data, benthic samples, and interpolation, it was critical to correlate the two kinds of interface data for verification in space.

If there was a one-to-one corresponding relationship between an acoustic class and a sediment sample or if each sampling site was precisely located at one ping footprint, then the acoustic classes could be tagged directly by the sampling sediment type and it would be unnecessary to do a statistical analysis. In most cases, however, there were different acoustic ping classes around one sampling site (see Figure 11). A major problem was the fact that the boat could not be moored precisely, and therefore a time lag occurred from the setting and the recording at the sampling sites using GPS to the actual performance (grabbing and probing). This spatial uncertainty between a benthic site and a to-be-verified acoustic class will always exist and in some cases, the acoustic classes were erroneously tagged by the not-precise-position of a benthic site. To reduce the misleading information caused by the inaccurate positions on the benthic sites, there were reliable sampling procedures. For example, in situ positioning visualization was used to calibrate QTC data using submersible observation (Anderson et al. 2002) and underwater photographs (Freitas, et al. 2003); benthic sampling from a moored boat (i.e., Freitas, et al., 2003), cameras, video TV and side scan (Hutin, et al., 2005, Wienberg and Bartholoma, 2005) have been performed. However, all this equipment rarely satisfied the accuracy expected even when the overlapping data sets were well organized in a particular study.

Since there is no equipment available to prevent some deeper uncertainty, a geo-statistical analysis is required and is based on interpolation theory: the nature of a point is more similar to nearby points than those farther away. For this thesis, it was possible to obtain the reliable verification of an acoustic class by identifying the most dominant substrate type close to an acoustically sampled site (nearest neighbour count) unless the associate distance was beyond a grid size (2 m) of interpolation (in other words, when the drift range of a grab or a descriptive bottom site was within 4 m^2 where only a substrate type was expected to exist). The advantage of this method demonstrated that one-to-one correspondence was no longer necessary. This simple rule was applied to most of the survey areas for the correlation of the acoustic classes and the benthic substrate samples. In the Red River upstream of the Floodgates survey, each of the acoustic classes was determined approximately by the highest frequencies around the sampling site that was labeled for its physical substrate type (nearest neighbor count). Three acoustic classes near each benthic site on the Red River upstream of the Floodgates were counted (Table 14). This counting method was used for data collected from the Winnipeg River. Three acoustic classes were verified directly by the benthic samples; Class 1, Class 3, and Class 4 were verified and found to be mixed the sand with the organic materials, pebble/gravel,

Table 14 Distribution of acoustic classes around sampling sites in the Red River upstream of the Floodgates*

Substrate type / Sampling site / Acoustic class	Coarse sediment/silty clay				Silty clay				Organic/silty clay	
	1	3	5	7	2	4	6	10	8	9
Class 1	20	0	0	0	0	0	1	1	6	2
Class 2	18	1	1	2	4	11	7	3	0	2
Class 3	88	25	9	14	2	1	1	3	2	3

* The highest number of each acoustic class for a sediment sample was used for verification.

Table 15 Distribution of acoustic classes around sampling sites in Numao Lake, the Winnipeg River*

Substrate type	Acoustic class	Class 1	Class 2	Class 3	Class 4
Rock	Site 4	102	0	0	0
	Site 5	61	0	0	0
	Site 16	31	0	0	0
	Site 38	32	1	0	0
	Site 39	42	0	0	0
Sandy/organic silt	Site 9	0	5	36	31
	Site 10	0	1	63	10
	Site 12	0	4	59	20
	Site 14	0	14	590	185
	Site 20	0	1	14	5
	Site 23	0	1	80	7
	Site 24	0	2	43	36
	Site 36	0	0	17	4
Silty fine/coarse sands	Site 1	0	26	2	42
	Site 2	0	12	0	95
	Site 3	0	15	5	91
	Site 6	0	21	0	74
	Site 7	0	82	0	203
	Site 8	0	53	56	115
	Site 11	0	7	7	48
	Site 13	0	14	0	44
	Site 17	0	85	8	187
	Site 18	0	5	2	58
	Site 19	15	18	0	64
	Site 21	0	0	14	28
	Site 22	0	0	14	31
	Site 25	0	34	0	198
	Site 26	0	6	13	32
	Site 27	0	4	1	24
	Site 28	0	6	2	21
	Site 29	0	4	1	5
	Site 30	0	1	0	8
	Site 31	0	4	1	12
	Site 32	0	8	0	23
	Site 33	0	20	0	30
	Site 34	0	6	9	58
	Site 35	0	0	17	22
	Site 37	0	9	0	33

* The highest number of each acoustic class for a sediment sample was used for verification.

and mixed sand (Table 15). Class 2 was not verified directly because no benthic sample was recovered because the rock or boulders were the dominant substrates in the center of the deep areas with strong currents.

The results of the neighbor count were confirmed by Correspondence Analysis (CA) and Principal Components Analysis (PCA) for both the Red River upstream of the Floodgates and Numao Lake surveys. The correlations between the acoustic classes and the substrate types were generally in accordance with the ones from the nearest neighbor count (Figures 53, 54), but were more predictable based on the Euclidean distance, particularly when a large number of benthic samples were available (e.g. in the Numao Lake) (Figure 54).

Figure 53. Correspondence Analysis on the acoustic classes and the sampling sites in the Red River upstream of the Floodgates
Note: these distinct substrate classes are clustered based on Table 15 (as described in details)

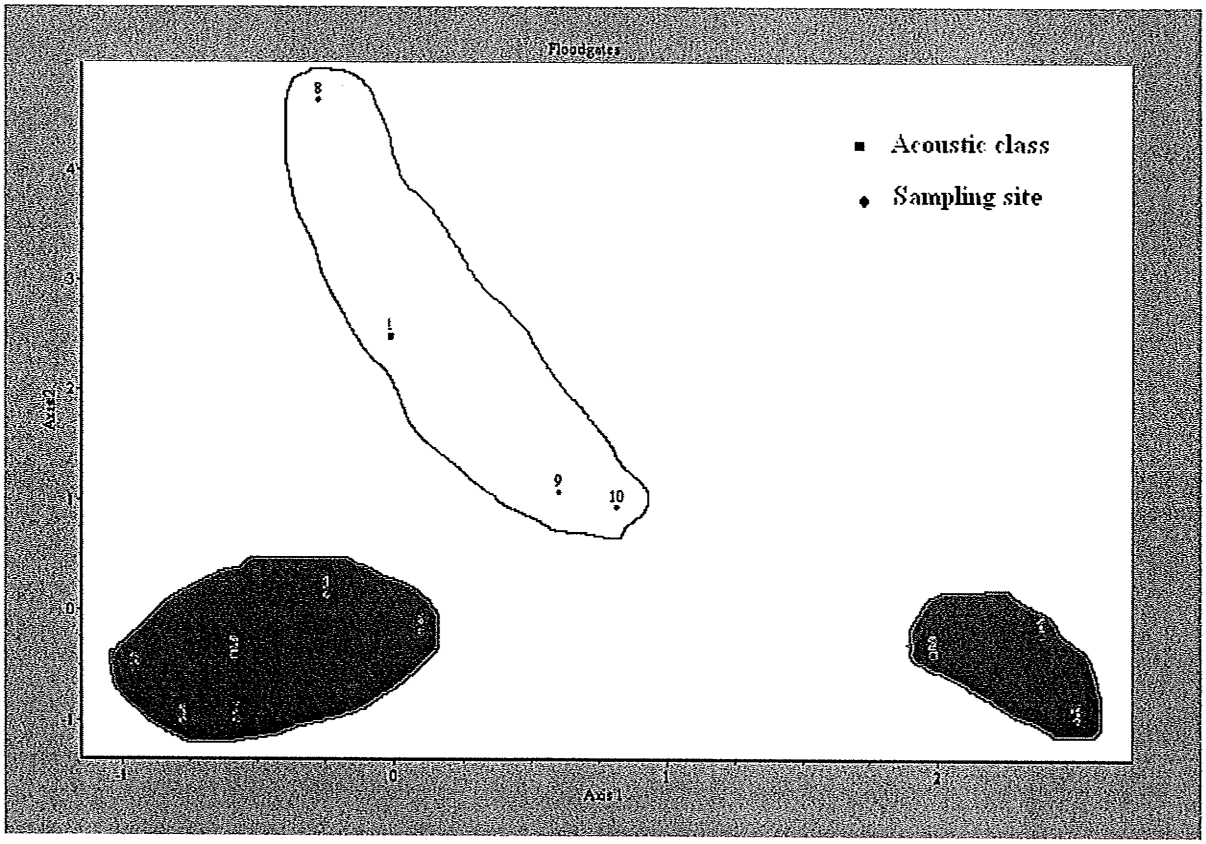
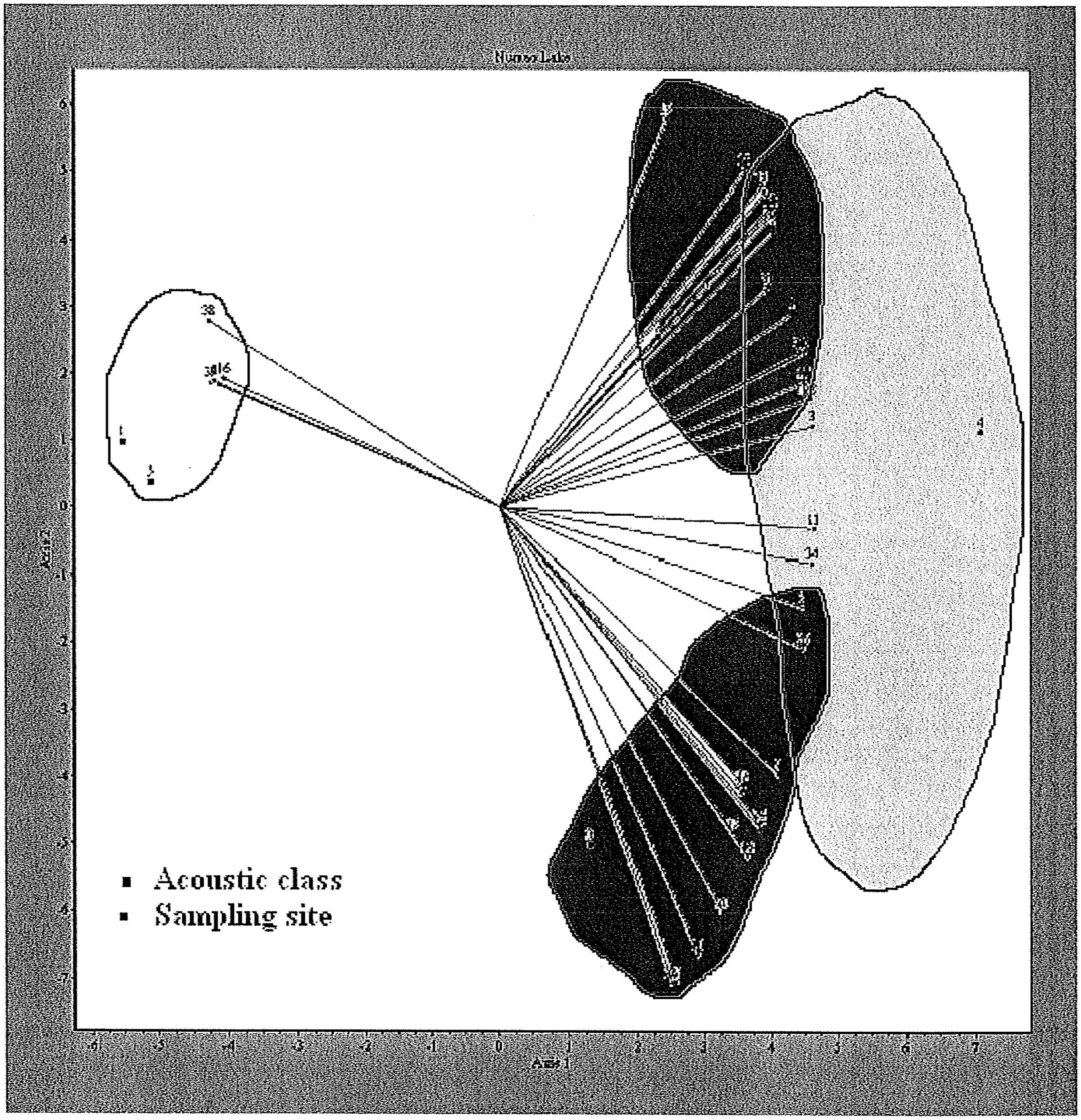

Floodgates
Acoustic class
Sampling site
8
1
9
10
Axis 2
Axis 1

Figure 54. Principal Components Analysis on the acoustic classes and sampling sites in Numao Lake, the Winnipeg River
Note: these distinct substrate classes are clustered based on Table 16 (as described in details)


Acoustic class
Sampling site

Comparison of direct verification and indirect verification

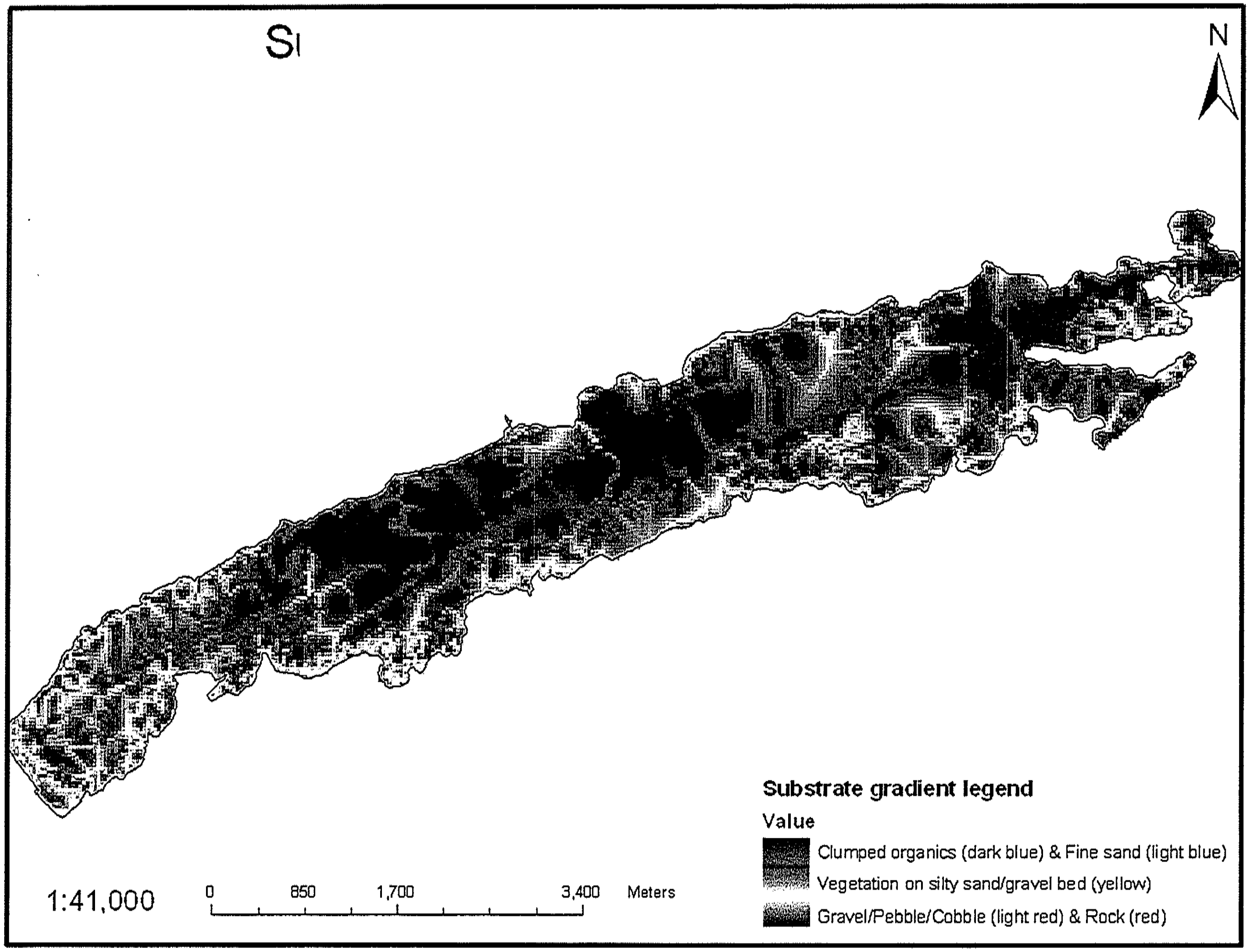
The acoustic classes and the substrate types were comparable between some lakes. Since no consistent values in the Q1 existed between Chitty Lake and Wormy Lake, the acoustic catalogue data from Falcon Lake and Stephenfield was referred to here. Falcon Lake was similar to Wormy Lake with respect to the four dominant sediment types and the Q1 values (Table 13). A common substrate type was clumped organic material for which Q1 values varied (-0.82597 and -1.1834 respectively) whereas, by contrast, the Q1 values of the three remaining substrate types such as the vegetation (-1.93944 and -1.9402), the pebble (-2.44029 and 2.53388) and the rock (-2.22849 and -2.19449) were much less variable. All the similarities were verified by direct verification and indirect verification. The QTC data from Falcon Lake was optimally split by the QTC software and verified by substrate types and is referred to as direct verification. As mentioned in the previous section (see P123 for details), the variation in the Q1 values is somewhat correlated with the substrate types, which means that the acoustic catalogue data for Wormy Lake may be applied to the FFV data (the pre-catalogue acoustic data) from Falcon Lake. This approach saves time as labour intensive ground truth is not necessarily followed by splitting in the QTC IMPACT. This process is defined as indirect verification. The comparison between the two approaches demonstrated that the spatial distribution of the substrate by the indirect verification (Figure 55) was consistent with that of the direct verification (Figure 56).

It is important to note that comparisons do not always work. The Q1 values of the four substrate types from Chitty Lake were on average larger than those from Wormy Lake with values of 05-0.6, although their physical states were similar. The distributions of two of the substrate types (boulder/rock and pebble/gravel) from Chitty Lake as were compared by the ground truth method (Figure 35, P135) were exaggerated by the correlating acoustic catalogue data from Wormy Lake while the clumped organic material was underestimated (Figure 57). Clearly, the Q1 values are a relative variable and sensitive to survey factors such as the sampling size, track spacing, boat speed, even depth and temperature, etc. The Q1 values represent the statistical information on the hardness and the roughness of the sea/river/lake bed. For example, the data from the soft clay and the clumped organic materials were identified in Stephenfield and Wormy Lake, respectively (Table 13), but they had similar Q1 values (0.90000) probably because of their hardness and/or smoothness. Consequently it is best to use the Q1 values to classify the unknown substrate types along with ground truth data.

An unresolved issue from this study is the relationship between the Q1 values collected from the QTC View Series 5 instrument and the actual substrates identified as rock, and boulders of various sizes. In some cases the Ponar grabs did not recover any substrate but when the bottom was observed by divers there were pockets of sand and silt between the rocks. Clearly more work is needed on these complex substrates that have rapidly changing regions of rock/boulders and sand/silt. It is predicted that with more intense studies on local regions with these types of substrates that some of this variation will be reduced and that more unique substrates will be classified.

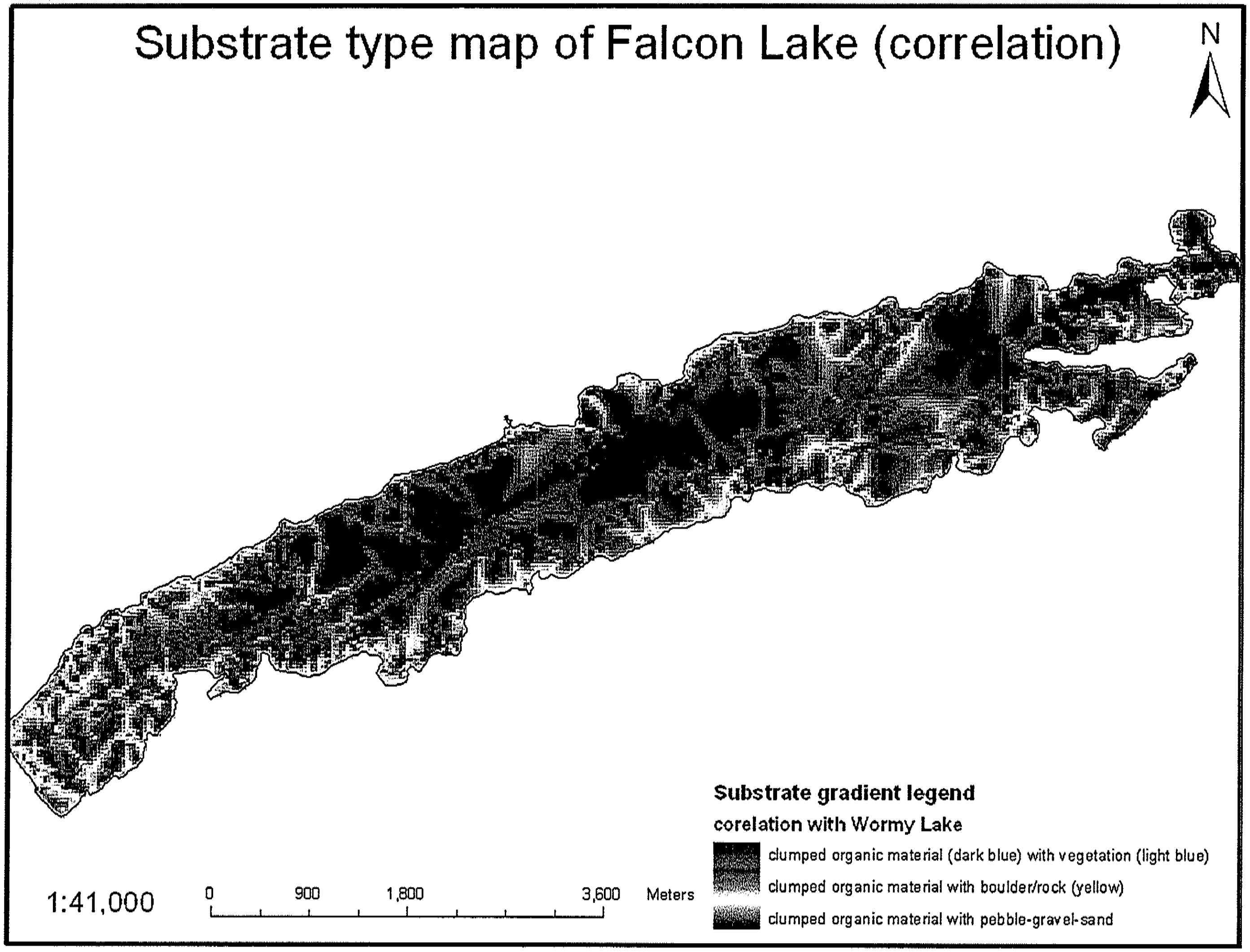
It is apparent from the comparative data relating to substrate classification that indirect verification should be applied with caution based on correlated the acoustic catalogue data only. In most cases, some ground truth will always be necessary. Nevertheless, even with the inherent limitation of the QTC View Series 5, extensive data was able to be collected rapidly and this data was used to build substrate maps by using up to 4 substrate classes of the lakes and rivers. Furthermore, the protocols for applying the acoustic data collected from the bottom of rivers and lakes to make interpolated GIS maps is available for the first time.

Figure 55. Substrate map Falcon Lake substrate map verified by direct observation Clumped organic material basically constitutes the lake bed. Rock/boulder and pebble/gravel are distributed in the shallow areas around the bank. Adjacent areas next to the pebble/gravel are vegetation. Pure clumped organic material is at the center of the lake.



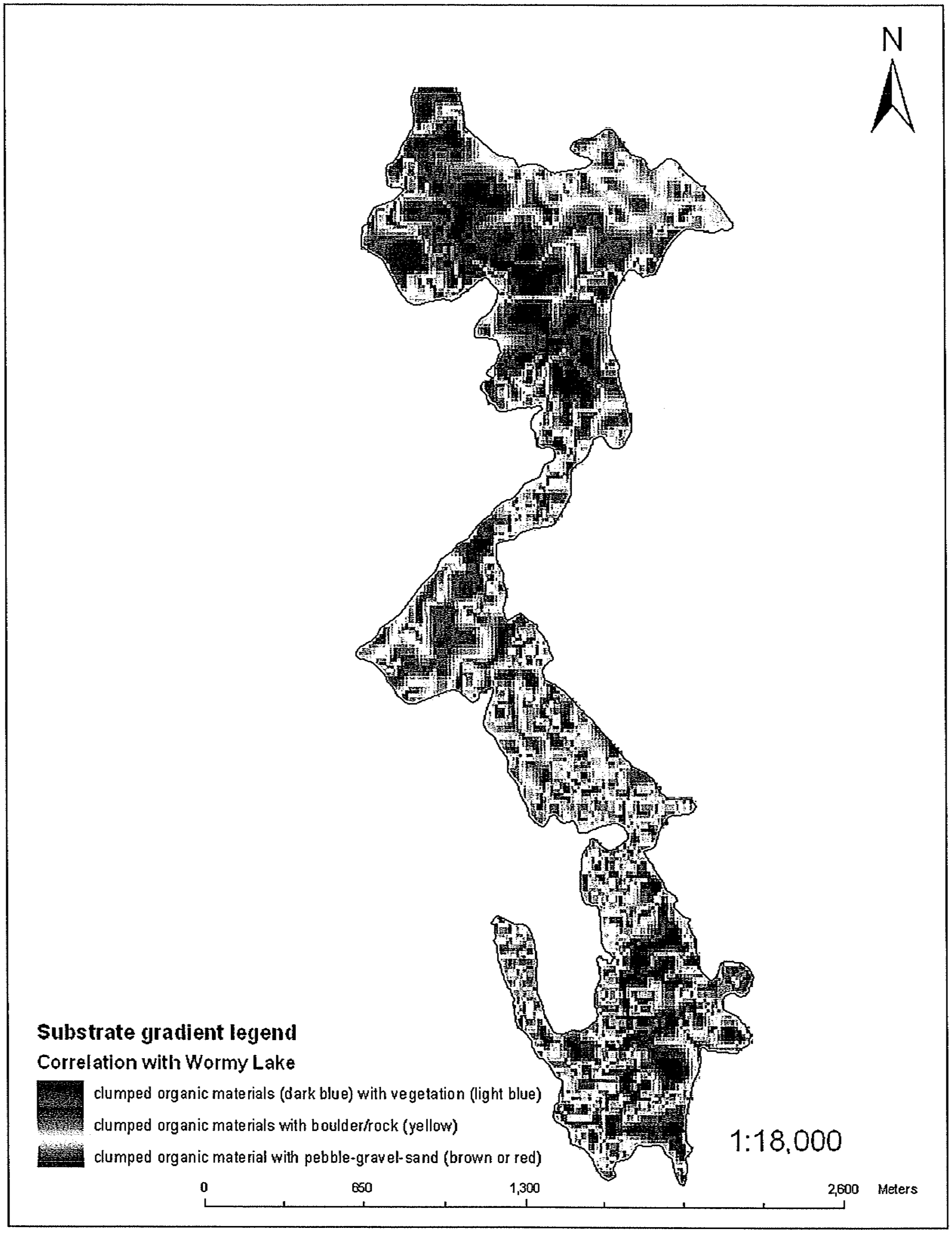
SI
N
Substrate gradient legend
Value
Clumped organics (dark blue) & Fine sand (light blue)
Vegetation on silty sand/gravel bed (yellow)
Gravel/Pebble/Cobble (light red) & Rock (red)
1:41,000
0
850
1,700
3,400
Meters

Figure 56. Substrate map of Falcon Lake (correlation) constructed by indirect verification
The substrate classes were correlated with the acoustic catalogue data from Wormy Lake, and were similar to the substrate classes verified by ground truth



Substrate type map of Falcon Lake (correlation)
N
Substrate gradient legend
corelation with Wormy Lake
clumped organic material (dark blue) with vegetation (light blue)
clumped organic material with boulder/rock (yellow)
clumped organic material with pebble-gravel-sand
1:41,000
0
900
1,800
3,600
Meters

Figure 57. Substrate map of Chitty Lake (correlation) constructed by indirect verification The substrate classes were correlated with the acoustic catalogue data from Wormy Lake Clumped organic material was underestimated when compared to the ground truth (Figure 35) while rock/boulder and pebble/gravel were exaggerated.


N
Substrate gradient legend
Correlation with Wormy Lake
clumped organic materials (dark blue) with vegetation (light blue)
clumped organic materials with boulder/rock (yellow)
clumped organic material with pebble-gravel-sand (brown or red)
1:18,000
0
650
1,300
2,600
Meters

Fish spatiotemporal distributions and habitat preferences

Rusak and Mosindy (1997) found that lake sturgeons moved the least in the winter. This type of data was not available in my study, but it was inferred from the fall movement patterns of the tagged fish (Figure 38, 41). The seasonal movements were examined and differentiated by simulating the location of the tagged sturgeons that were tracked and downloaded regularly from VR2 receivers. The coherence of the observed patterns over years, and the fidelity of the sites, also provided support for definite seasonal movements in Lake of the Woods and Rainy River which is part of Winnipeg-Nelson river system, Ontario (Rusak and Mosindy 1997).

The results of many studies demonstrate that lake sturgeons are a benthic species (Binkowski and Doroshov, 1985) that feed on benthic macro-invertebrates (McKinley et al. 1993) on sand and clay (Chiasson et al. 1997). As the part of this project links between lake sturgeon movements relative to habitats in the river and lake environments, to water depth and acoustic classes were interpolated to maps dealing with the bathymetric variation and substrate patterns in GIS. Using a simulation program that roughly calculates the geo-positions based on triangular algorithms, the movements of lake sturgeon were plotted on the interpolating maps of the bathymetry and substrate pattern at Seven Sisters (Figure 42, 43), the section of the Winnipeg River. The final layers were integrated to show the habitat preferences with the bathymetric variation and substrate patterns.

The lake sturgeon movement at Seven Sisters on the Winnipeg River utilizes the VEMCO VR2 receivers. These receivers are relatively inexpensive to purchase and easily deployed but the information recovered is limited to the presence or absence of a tagged fish within the range of a given receiver. This study was associated with a severely modified river bed, i.e., flows through the turbines and over the spillway but these flows varied, depending on the time of a year and the amount of precipitation in the region.

Four sturgeons of various sizes were used to compare their movement patterns within the Seven Sisters from July 26th to October 31st (Figures 43, 44). Based on the data it appears that the larger fish (> 5000 g) moved more actively than the smaller ones, but their overall ranges were similar. Except for the smallest fish (1071 g), the concentration of lake sturgeon movements occurred in a narrow zone of the river. The substrate in this area consisted of mostly sand at a depth of 3 – 4 m.

Lake sturgeons usually inhabit waters from 4 to 9 m in depth (Houston, 1987). Most wild sturgeons have been found over mud bottoms in earlier studies. Recently, there has been an increased interest in supplementing the populations with hatchery-reared fish. Research on the substrate preferences of juvenile hatchery-reared lake sturgeon has clearly indicated that they were strongly attracted to the sand substrate (Peake, 1999). All of the released sturgeons (juvenile and subadults) in this study were hatchery raised and their substrate selection was similar.

Lake trout, on the other hand, exhibit a highly mobile predation strategy that is dependent upon the location of the prey species relative to the bottom (Martin and Olver, 1980). The distributions are not strongly associated with the bathymetry and the substrate types because the trout is a pelagic species (Martin and Olver, 1980). Their spatial movements are characteristic of below the surface water depths and temperatures. Lake trout are most abundant between 15 and 30 m (Martin and Olver, 1980) and this depends on size, depth, and temperature of the lake. There are two deep "holes" in Chitty Lake, with the deepest occurring (42m) in the north basin. No deeper detections (more than 16 m) were found between July and October, 2004 in the lake, and were probably stratified thermally. Lake trout prefer the deeper water (12-15 m) and there is strong fidelity to the region of the lake from which they were captured. None of the tagged lake trout moved between the basins nor was there movement between Chitty and Alexie Lake over the winter, even though there was open water between the lakes.

Extensive field observations concluded that the young nonanadromous char are benthic in their alevin and late juvenile life. As they grow larger they change from benthic to pelagic (Johnson, 1980). The fork length and body weight of the released char ranged from 210 to 625 mm and from 95 to 2200 g respectively. It is reckoned from most catch curves reported (Johnson, 1975a) that they were in the transitional period from benthic to pelagic. Movement studies found that small char moved into shallow areas while larger char remained in the deepest areas of the lake (Figure 48).

Data on all of the freshwater species used in this study suggests a strong site fidelity. A simulation program, based on the auto-acquisition system, generated approximate geo-positions between two adjacent VR2 receivers as they do not give directional location data. This is a good approximation of location as it averages the position of a fish movement between any two receivers that pick up the tag signal. Consequently, the core areas of a fish movement could be estimated approximately in terms of the kernel density plus the frequency of use (Figures 42, 48, 50). Interestingly, the core areas were predictable and there appears to be strong site fidelity for these species of fish. It is concluded from a preliminarily analysis that the movements of lake surgeons are correlated to some extent with water flow and distributions of lake trout and Arctic char are influenced by the water temperature.

CONCLUSIONS

The purpose of this thesis was to apply the QTC VIEW Series V as a research tool to describe fish habitat, namely bathymetry and substrate. Additional objectives included the management and manipulation of very large data sets in order to develop geographic information system maps as there were no available computer programs. The comparative aspects of the research were important as QTC VIEW Series V equipment has several limitations.

The integration of fish movement data into geo-referenced maps required some novel approaches since neither of the two technologies, i.e. habitat/substrate mapping nor the sonar tagging systems provided ways to integrate the data. This is especially true for the Vemco VR2 receivers as they were designed to record a fish as it passed by a receiver. The computer algorithms developed for the thesis have advanced the way fish movement can be analyzed and additional data management has enabled the fish movement data, albeit at a coarse scale, to be integrated into GIS.

Specific conclusions from this thesis are:

1) A rapid and predictable way to create acoustic catalogue of substrates (substrate classes) can be achieved when QTC VIEW Series V is used to collect acoustic data. A post processing algorithm on the acoustic data is specifically designed to extract water bottom attributes in QTC IMPACT. This processed data provides a large set of accurate depths and discrete substrate classes for a given survey area. Up to five substrate classes can be discriminated, but need to be identified by ground truth that combines visual inspection. Classification based on sieving data has some merits, but does not correlate with acoustic data as the overall integration of the substrate has been altered

2) Different substrate classes were represented by three Q values in acoustic catalogue data in which Q1 values were the most weighted distance values. Variation in Q1 values was related to substrates from benthic sites.

When Q1 values were similar in Wormy Lake and Falcon Lake, the substrate types were also similar, i.e. pebble and rock, but these correlations were not always reliable and sometimes similar substrates in different water system presented different Q1 values, i.e., the Q1 values of rock from the Winnipeg River and Chitty Lake were not similar.

3) Acoustic signals characterized extensive homogeneous substrates such as silt/clay, sand, pebble/gravel, but occasionally gave a "fuzzy' signal and the signal could not differentiate between hard substrates, i.e., rock, boulder and hard clay, or fluid, soft substrates containing up to 90% water, and bubbles near bottom or floating substrate, i.e. vegetation and suspended materials. In some instances, the bottom features were misidentified by acoustic signals when it was very deep with a soft bottom i.e., the north basin of Chitty Lake.

4) Spatial uncertainty existed between acoustic track points and benthic sites. Nearest neighbor count was primarily used to verify acoustic classes with substrates from benthic sites and field observations, but multivariate analyses such as CA and PCA were also employed to correlate acoustic classes with substrate types on the Red River upstream of the Floodgates and Numao Lake on the Winnipeg River.

5) In most cases, benthic samples were used directly to decide how many acoustic classes to split in order to identify substrate types (direct verification). It will not be necessary to split the acoustic data and to apply ground truth if acoustic catalogue is properly constructed and verified by direct observation. This method was defined as indirect verification in my thesis. Use of the indirect method should be applied with caution unless the conditions (geological and flows) of the two survey areas are known to be similar.

6) Topogrid was applied to interpolating acoustic catalogue data for areal mapping of bathymetry and substrate because this technique has high

numerical accuracy, generates a clean surface and smooth contour lines for bathymetry, discriminates substrates based on hydrological conditions. RMSE was used to evaluate the numerical accuracy of four interpolation techniques (Topogrid, TIN, Kriging and IDW) in this study.

7) Bathymetry was accurately mapped using Topogrid while the number of substrate classes was limited due to the uncertain variation of Q1 values. More work is necessary to evaluate correlation of Q1 values with verified substrates, but data to date suggest some correlations.

8) The resolution of fish detections by the Vemco VR2 receivers was better with improved data management and the application of a computer program to simulate the data collected from fish movements. Although patterns on fish movement are at a course scale our knowledge has been extended beyond the simple detection of a tagged fish.

9) Simulation of movement patterns of lake sturgeon, lake trout and Arctic char demonstrated that these three species have strong site fidelity. Seasonal movement patterns of lake sturgeon were described from the summer of 2004 to the fall of 2005. The movement of lake sturgeon was closely associated with specific depths and substrate classes. A higher frequency of detections was found at 3-4 m over sand substrates with flows of 690 cms to 1050 cms.

   There appear to be two populations of lake trout at Chitty Lake and swimming depth were affected by water temperature. Arctic char preferred deeper water during the open water period.

10) Habitat used by lake sturgeon, lake trout and Arctic char were defined and interpreted from fish movement patterns, and core areas delineated, by correlating fish seasonal movements with environmental variables such as depth, water flow, temperature and substrate type.

RECOMMENDATIONS

1. QTC VIEW is useful to study coarse scale and/or regional evaluation of substrates, but still needs refinements. These refinements include:
   a. Further analyses of the QTC data, e.g., Q1 values need to be compared to actual substrate samples collected by benthic grabs.
   b. Methods to collect data needs improvement, i.e., much slower boat speed will be required to obtain more data points over smaller area and are especially recommended for complicated substrates, i.e., mixture of boulder and sand or bed rock and boulders.
   c. Distance between transects should be reduced to 1- 2 m to improve resolution, but hopefully as catalogues improve this level of data collection can be reduced.

2. Primary data and large numbers of intermediate data products should be well organized and stored in a database management system.

3. While the simulation of fish movement has changed the application of VR2 receivers from a simple fish counter to a system that determines an average location between the receivers i.e. the overlap of two or three concentric circles, the end result is still at a coarse scale. Tags need to be developed with a much shorter detection radius (lower battery power i.e., probably in the order of 100 to 200m) to improve resolution of fish movements.

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