Use of Remote-Sensing Techniques to Survey the Physical Habitat of Large Rivers

Contribution number 983 of the Great Lakes Science Center

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U.S. GEOLOGICAL SURVEY

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Great Lakes Science Center

Ann Arbor, Michigan
1997

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBIT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information write to:

U.S. Geological Survey
Great Lakes Science Center
1451 Green Road
Ann Arbor, MI 48105

Copies of this report can be purchased from:

U.S. Geological Survey
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FIGURES

CONVERSION FACTORS

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
kilometer (km)	0.5400	mile, nautical
meter (m)	1.094	yard
Flow rate		
kilometer per hour (km/h)	0.6214	mile per hour
meter per second (m/s)	3.281	foot per second
foot per second (ft/s)	0.3048	meter per second
Area		
square meter (m^2)	10.76	square foot

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ABSTRACT

Remote-sensing techniques that can be used to quantitatively characterize the physical habitat in large rivers in the United States where traditional survey approaches typically used in small-and medium-sized streams and rivers would be ineffective or impossible to apply. The state-of-the-art remote-sensing technologies that we discuss here include side-scan sonar, RoxAnn[1], acoustic Doppler current profiler, remotely operated vehicles and camera systems, global positioning systems, and laser level survey systems. The use of these technologies will permit the collection of information needed to create computer visualizations and hard copy maps and generate quantitative data bases that can be used in real-time mode in the field to characterize the physical habitat at a study location of interest and to guide the distribution of sampling effort needed to address other habitat-related study objectives.

This report augments habitat sampling and characterization guidance provided by Meador et al. (1993) and is intended for use primarily by U. S. Geological Survey National Water Quality Assessment program managers and scientists who are documenting water quality in streams and rivers of the United States.

INTRODUCTION

This report provides a brief overview of state-of-the-art techniques and equipment that can be used to quantitatively describe the physical habitat in large rivers and in deeper, non-wadeable reaches of medium-sized rivers in the United States. It focuses on remote-sensing approaches that can be effectively applied in situations where more traditional survey approaches typically used in small- and medium-sized streams and rivers would be ineffective or impossible to apply. For this report, streams and rivers are defined as small, medium, or large, based on a wadeability criterion that is applied under normal (summer) low-flow conditions. The small stream can be crossed anywhere by wading. The small stream extends from its headwaters downstream to the first point where it cannot be crossed by wading; at this point it becomes a medium-sized stream or river. The medium-sized stream or river can be crossed in places by wading. It extends downstream to the last point where it can be crossed by wading; below this point it becomes a large river. The large river cannot be crossed anywhere by wading.

The remote-sensing technologies that we discuss here include side-scan sonar (SSS); RoxAnn (RA); acoustic Doppler current profiler (ADCP); submersible video camera systems, some of which are carried by a remotely operated

[1]Mention of brand names is for identification purposes only and does not constitute endorsement by the U. S. Government

vehicle (ROV); global positioning systems (GPS); and laser level survey systems (LLSS). These technologies are recommended because they can be used safely and economically to describe the physical environment in large rivers and provide a quantitative data base from which reliable characterizations of the physical habitat can be developed. They are especially well-suited for providing rapid coverage of the larger areas of river bed that must be surveyed in large rivers. These remote-sensing technologies also work well in the deep water found in large rivers. In small rivers and shallower portions of medium-sized rivers, observations can be made from the bank or while wading, and sampling sites can be identified and visited in the same manner. In large rivers, sampling sites in littoral areas also sometimes can be identified visually from the bank, while wading, or from a boat deck, but in deeper waters this becomes more difficult or impossible. In these deepwater environments, remote-sensing technology can be used effectively to create a visual, quantitative display of the physical habitat. The more sophisticated technologies can also process and display the data being collected so that it can be used immediately in the field to guide the distribution of sampling effort needed to meet other habitat study objectives.

REMOTE-SENSING TECHNIQUES

This section of the report describes state-of-the-art remote-sensing tehniques that can be used for surveying surficial substrates and for measuring current velocity in large rivers and in the deeper, nonwadeable sections of medium-sized streams and rivers. These approaches typically involve a primary system element such as SSS, RA, and ADCP to collect, store, and process the data; GPS to provide location information to permit geo-referencing of the data; LLSS to measure distances and elevation; and a computer-based geographic information system (GIS) to further process and display the data in map, other graphic, or digital form. Submersible video camera systems, some of which are carried by an ROV, are commonly used to explore and document underwater environments and biota and to verify the results of surveys conducted with other remote-sensing technologies.

Side-Scan Sonar

The first operable SSS was built in the late 1950s and this technological break-through made possible the rapid, systematic study and large-scale mapping of surficial features in the marine environment (Flemming, 1976). Recent advances in SSS technology have resulted in the production of relatively inexpensive survey-quality systems that are well suited for inventory and mapping in freshwater environments.

The basic system includes a towfish, a data processing unit with strip-chart recorder, and a tape deck (figure 1) (Edsall, 1992). The towfish, which is towed behind the survey vessel on an electronic tether, directs a fan-shaped beam of acoustic energy towards the bottom of the water body in a plane normal to the towing direction (figure 2). The beam impinges on the bottom directly beneath the towfish and out to some preset distance on either side. The echo from this acoustic signal is received by the towfish, transformed into an electrical signal, and transmitted to the processing unit. There the signal is converted into strip-chart output in which the substrate surficial features are shown in plan view (figure 3). Water depth directly beneath the towfish track is also recorded on the strip chart. The data on which the strip chart is based are also stored on tape in the tape-deck element. Loran-C or GPS location data from a free-standing receiver are recorded manually on the strip chart record at 2–3-minute intervals to allow the record to be geo-referenced.

River surveys are conducted by towing the towfish behind the survey vessel at a constant speed over bottom in an upstream direction roughly parallel to the thalweg. This approach was used by the Michigan Department of Natural Resources and the Great Lakes Science Center in July 1996 to document substrates believed to be used for spawning by lake sturgeon (*Acipenser fulvescens*) in the North Channel of the St. Clair River, Michigan (figure 4). If more than one transect is needed to record the entire stream channel from one bank to the other, parallel transects are recommended. These transects should be spaced so that the edges of records of the ensonified bottom for adjacent transects overlap by about 30 percent. A "mosaic" map (figure 5) can be assembled from the records for

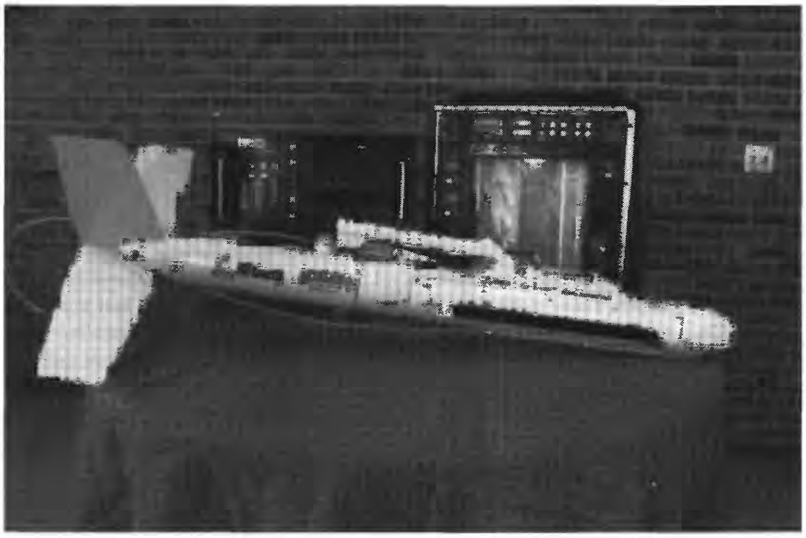


Figure 1. Side-scan sonar equipment used by the Great Lakes Science Center. The towfish is in the foreground and the tape deck and microprocessor (showing strip-chart output) are in the background.

adjacent, parallel transects.

Side-scan sonar sampling power varies with towing speed and the swath width selected for use. The 100-kHz EG&G system shown in figure 1 provides good records of major substrate types (sand, <2mm in diameter; gravel, 2–64 mm; rubble, 65–256 mm; cobble, 257–999 mm, and boulders >999 mm) when it is towed at about 7–8 km/h and the swath width is set at 200 m. Individual rocks about 0.3 m in diameter and larger and other high density bottom features of similar and larger size can be discerned in these records. Higher resolution is possible with 500-kHz systems that require lower towing speeds and narrower swath widths. The basic system shown in figure 1 can be used effectively in water as shallow as 2–3 m and the maximum depths in large North American rivers are well within the operating range of the system.

The strip-chart output, which resembles an aerial photograph, is interpreted by inspection and review of ground truth information that is typically provided by a remotely operated underwater camera system (see figure 3). The strip chart record reflects both the material properties of substrate components and the topography of the bottom. Images of rock are darker than those of sand and mud. Steep slopes facing the towfish reflect stronger echos and produce darker images than slopes that are less steep or that are falling away from the towfish. Free-standing objects, such as large rocks or woody debris produce a dark image on the side facing the towfish and a lighter "acoustic shadow" on the side facing away from the towfish. A number of these substrate features are identified in figures 3 and 4. Submersed and emergent aquatic vegetation can be seen on the strip-chart record and, in shallow water, dense submersed vegetation that reaches the surface of the water can obscure the record. In deeper water or where plants do not extend far above the bottom, the plant beds can be easily delineated on the record (figure 5). Unpublished observations made in the St. Clair–Detroit River system suggest that it may be possible to distinguish different plant communities on the basis of their growth form displayed on the strip-chart.

The strip charts can be used to illustrate the substrate distribution in the study area and to locate features or areas for additional study or sampling. The areal extent of each substrate distribution can be quantified by manually delineating the distribution as a polygon and then digitizing the polygon using a GIS with PC ARC-INFO and PC TIN or other similar software. If several overlapping strip charts are produced, a mosaic map can be assembled by overlaying them manually in a geo-referenced manner. Substrate distributions can then be delineated across the entire mosaic and a geo-referenced substrate map can then be produced from the mosaic (figure 6) by a GIS. Water depth along each towfish track

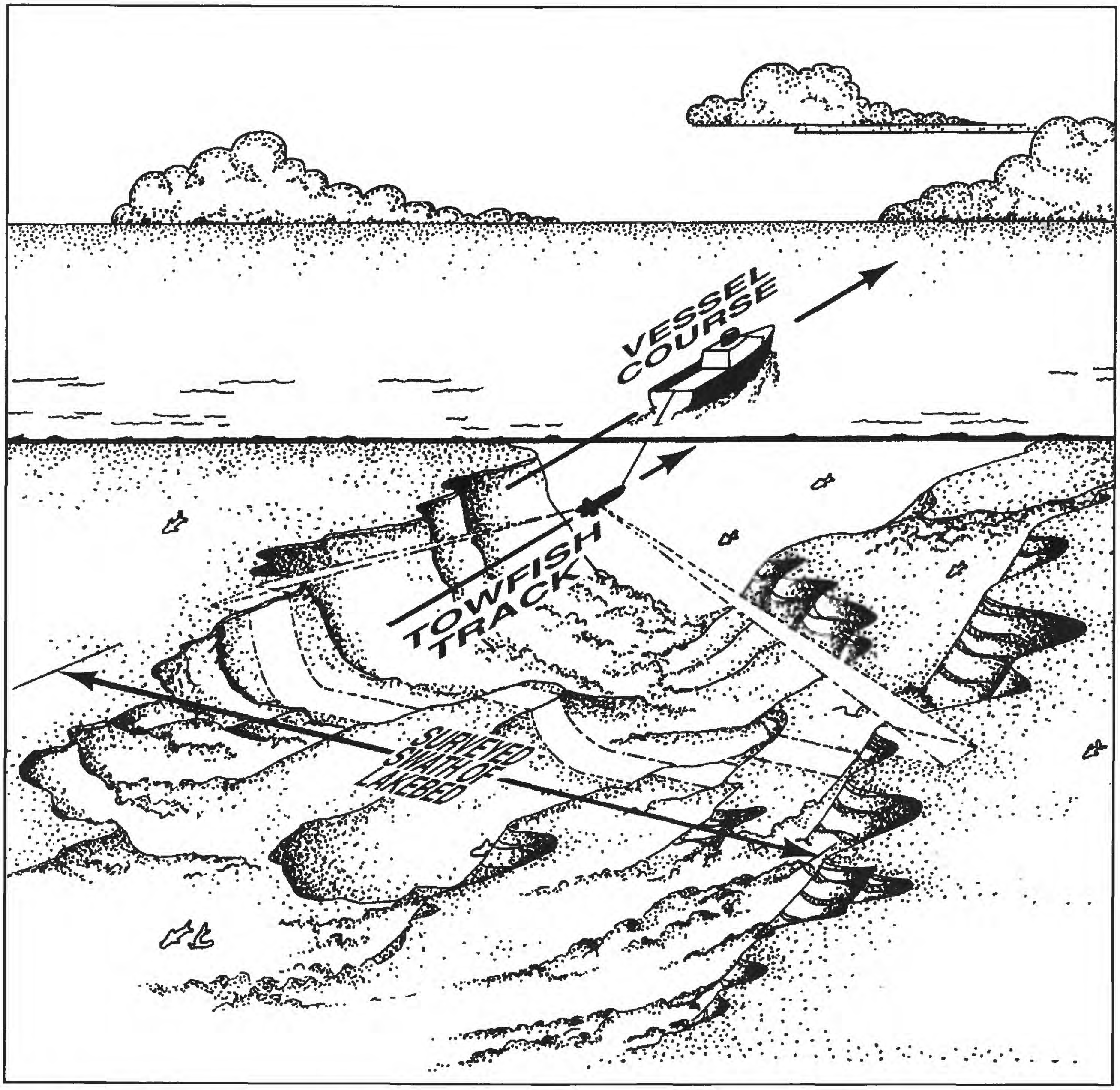


Figure 2. Surveying the waterbody bottom with side-scan sonar.

can be added to the mosaic as an annotation, and if there are enough depth data, depth contours can be developed, digitized, and added to the computer-drawn map, as in figure 6. Map production is discussed in more detail and examples are given in the published literature (Edsall, 1992; Edsall and Kennedy, 1995; Edsall, et al. 1989, 1991, 1993).

The newest systems are replacing or supplementing the strip-chart output with electronic imaging output on a video monitor and linked GIS hard-copy output. The MIDAS digital system (EG&G Marine Instruments, 1994; EdgeTech, 1996) , and the SIPS image processing system (Gourley, 1996) are examples of this new technology. These systems can create electronic mosaics, thus eliminating the need for manual mosaicing using strip-chart output. Because data acquisition and storage is GPS linked in these systems, survey transects do not need to be straight lines; the system corrects the data set and displays it in a rectilinear manner with proper

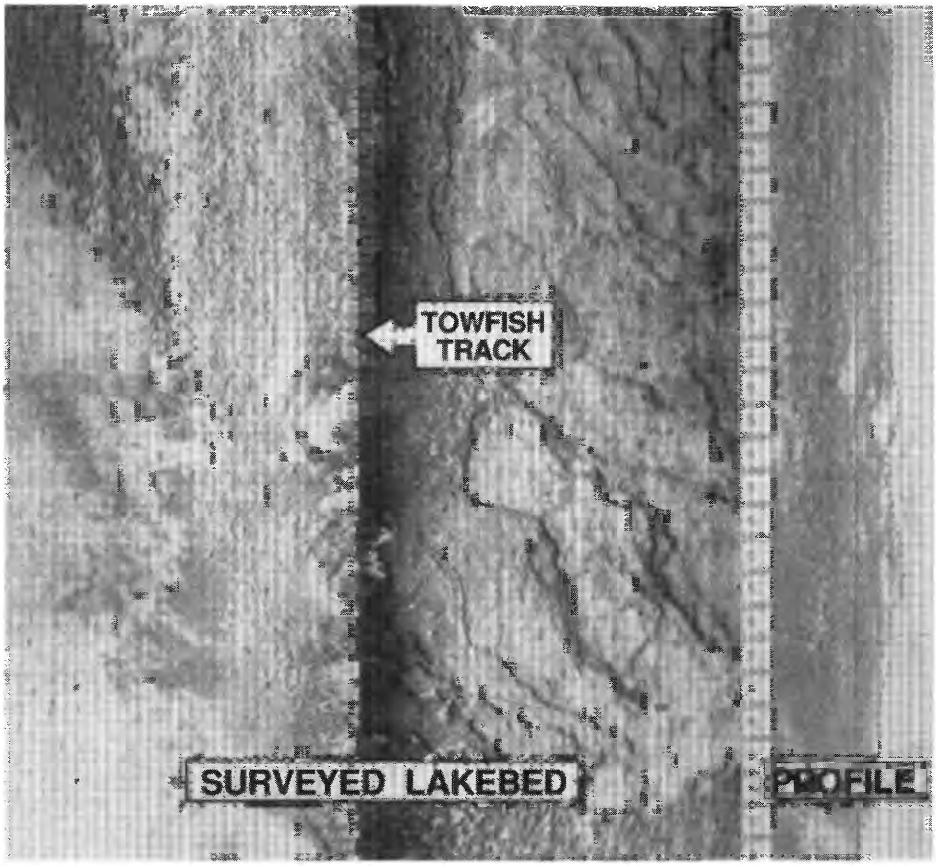


Figure 3. Microprocessor strip-chart record showing a 200-m wide swath of surveyed lake bed, which is composed of rugged, stepped, bedrock ridges. The towfish track is the thin line that extends vertically across the face of the record (see also Figure 2). The profile portion of the record shows the water depth along the towfish track.

Cartesian coordinates. The SIPS portion of the MIDAS SSS system permits substrate classification criteria developed from ground truth observations to be applied to the SSS data to automatically identify substrate types and to delineate their distributions.

The more sophisticated SSS systems permit the data to be displayed immediately in graphical form to aid the researcher in the field. For example, to facilitate mapping, a plan view of the survey vessel track and the swath of water body bottom that has been surveyed is shown in real time on the video monitor. This feature helps the researcher ensure that all areas of interest at a study location have been surveyed. These systems also have a variety of other features that facilitate data collection and improve the quality of the data collected. The MIDAS system, for example, uses a towfish that simultaneously collects substrate information in both the 100- and 500-kHz modes and integrates them to provide a composite record that has some of the higher object resolution capability of the 500-kHz operating mode, while retaining the greater sampling power (200-m swath width and 7–8 km/hr towing speed) of the 100-kHz operating mode.

The basic side-scan sonar system used in the St. Clair River survey described above costs about $60,000. A new system that includes SIPS and MIDAS will cost about $100,000; that system requires a GPS, which is not included in the cost estimate. Information on GPS systems and costs is given in the following section.

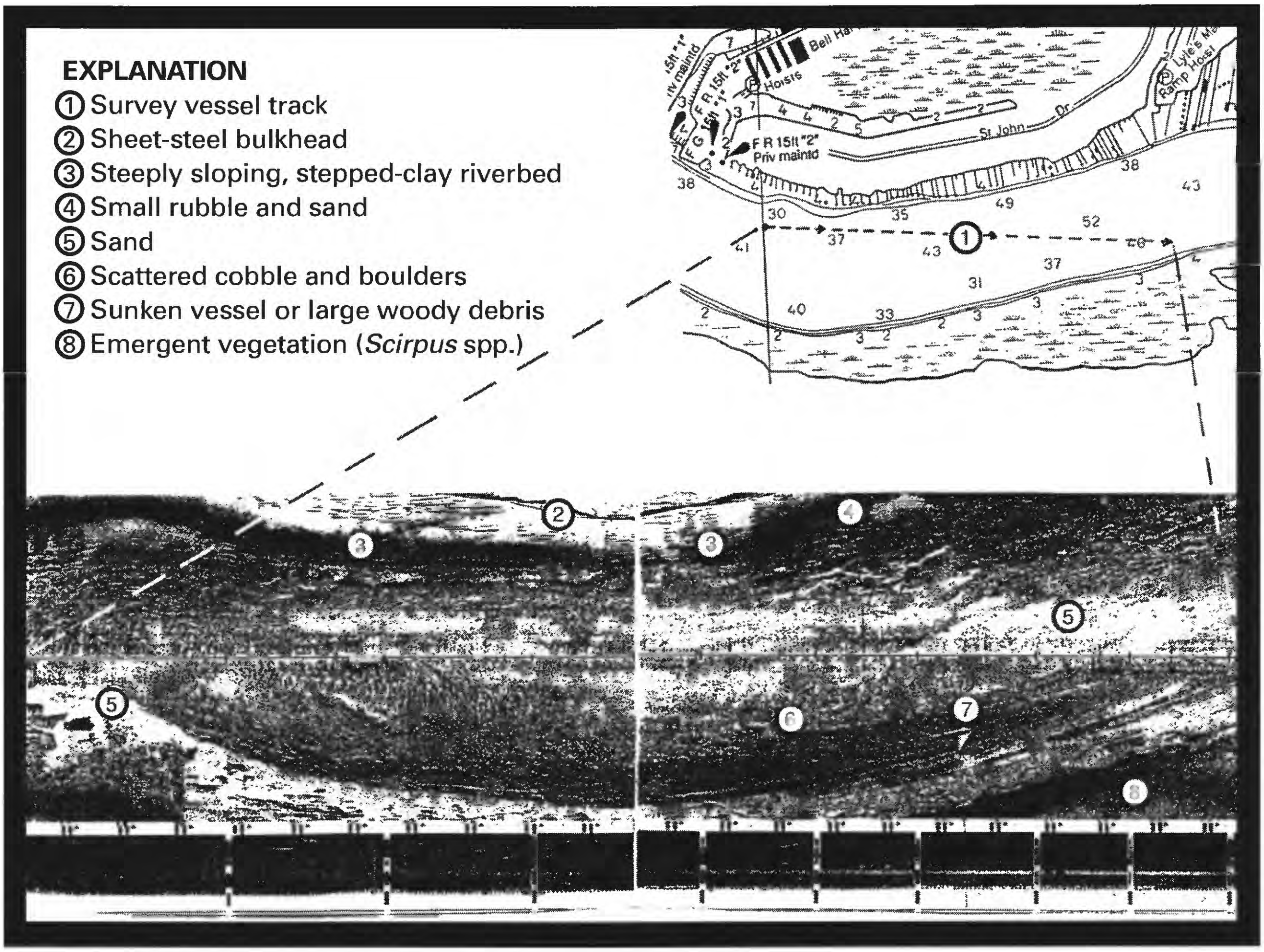


Figure 4. Side-scan sonar strip-chart record of the North Channel of the St. Clair River, Michigan. An excerpt from a navigation chart for this reach is shown for reference. The river is about 300 m wide at this point; water depths on the navigation chart are in feet; flow is from right to left.

RoxAnn

RoxAnn is a new system that can use acoustic data from any of a variety of conventional, single-beam echo-sounders to rapidly and objectively classify and map water body Surficial substrates. RoxAnn discriminates between water body substrate types and outputs the data in a quantitative form ready for instant or later computer processing. RoxAnn can be used with a preexisting echo-sounder and is also available from the manufacturer as a fully portable system with its own echo-sounder. A technical description of the system is given by Chivers et al. (1990) and an update is provided by Murphy et al. (1995). The system components are the echo-sounder transducer and processor-recorder; RA, which includes a head amplifier and parallel receiver housed in compact cases; and a personal computer (PC) for data acquisition, storage, and display. The data from the RA can be exported as an ASCII file to a computer with ARC INFO software for processing and the production of substrate maps in various display modes.

RoxAnn uses the first and second echos from a single transmission of the echo-sounder to collect information on the surficial substrate. The first echo (E1) provides a numerical index of substrate roughness and the second (E2) of hardness. When the RA is used with Hypack for Windows software, these values are displayed as x- (E1) and y- (E2) values, on a Cartesian grid in the RA "color box" on the shipboard PC color-video monitor (figure 7). This grid is divided into substrate material types that are assigned unique colors.

Classification can be carried out in two ways—by matching or by calibration. In the first,

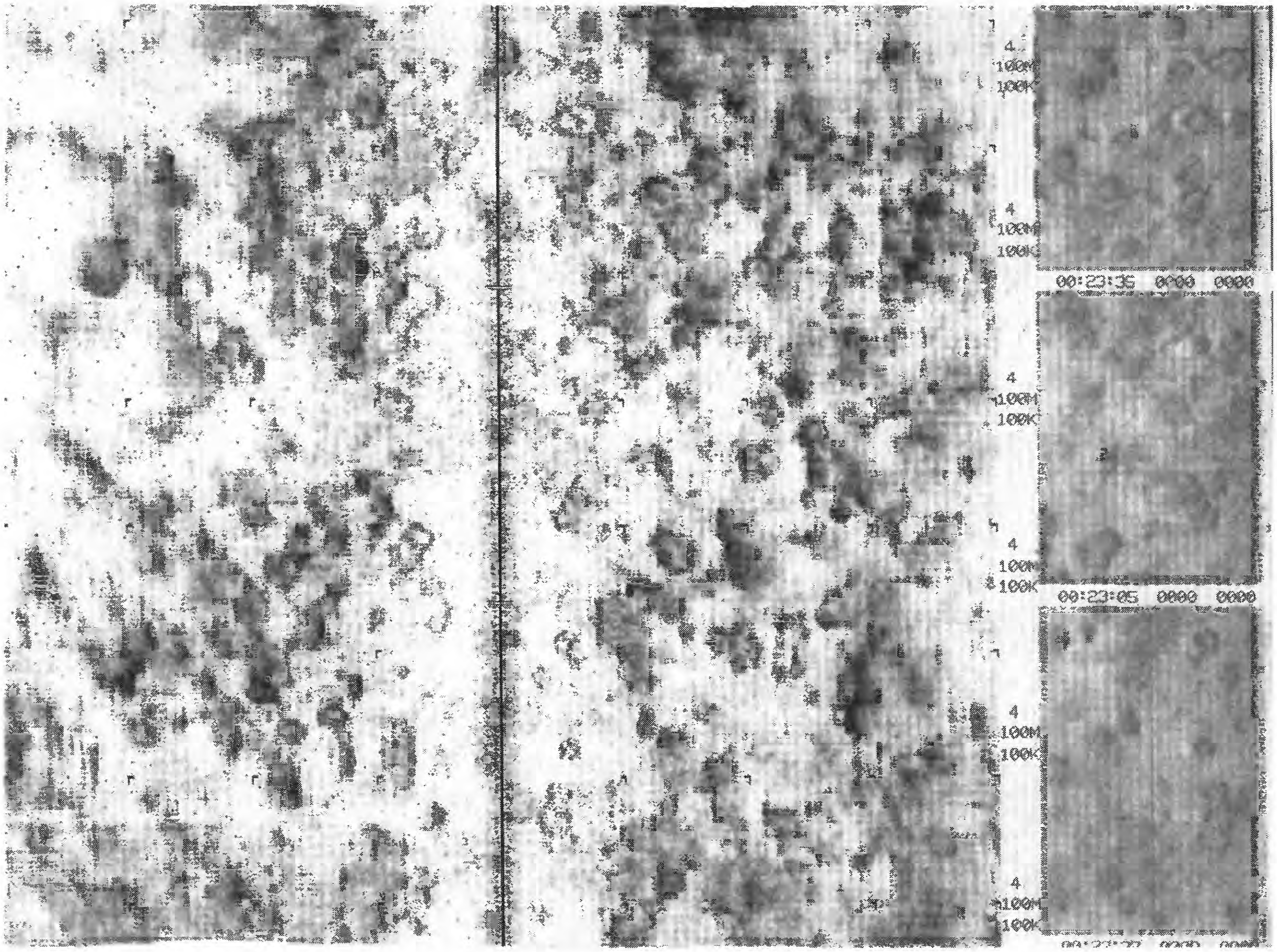
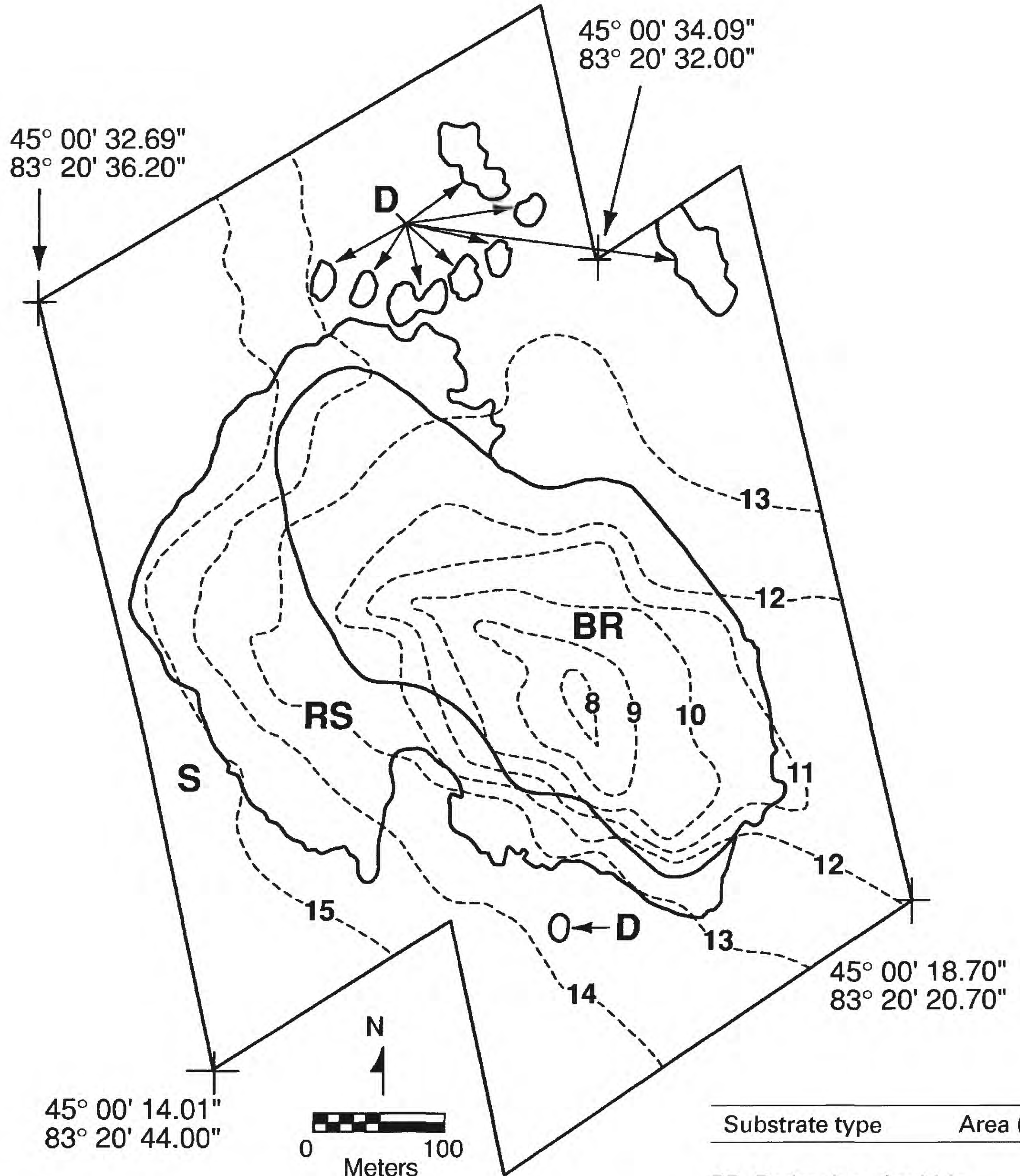


Figure 5. Side-scan sonar strip-chart record showing a submersed aquatic plant community in Lake St. Clair. Tall plants (e.g., *Potamogeton* spp.) are shown as dark clumps and short plants (e.g., *Chara* spp.) as lightly shaded background; nonvegetated lake bed is white.

discrete ranges of E1 and E2 values are each automatically assigned specific colors. The survey data are collected and stored on disk until they can be matched by ground truthing with known physical criteria such as substrate particle size (e.g., mud, sand, gravel, rubble, cobble, boulders, bedrock), biological criteria (e.g., mussel beds, submersed aquatic plants), or both. In the second, ground truth information is used to calibrate RA color boxes by redefining the ranges of E1 and E2 values, so that functional classifications consistent with user need, can be assigned to them. In this approach, the survey vessel is positioned over a known, discrete substrate of interest for collection of data. The ground truth data are collected and the color box is changed to fit the data display; that substrate will be automatically identified and shown by that color whenever it is again encountered. Other substrates of interest that are likely or known to occur in the survey area can be similarly referenced. This calibration process precludes the need to make subjective interpretations of the data and is one of RA's strongest features. The system is flexible and references can be changed easily at a later date as needed, for example, by combining boxes, enlarging or shrinking boxes, or by developing a set of new boxes within a single original box. The system can also be operated in a "search" mode to display a single, referenced substrate type of interest (e.g., bedrock) against a background of all other types combined.

Standard sediment particle-size discriminations for habitat classification are easily made with RA. Subtle biological classifications are also possible. For example, the RA manufacturer



Substrate type	Area (hectares)
BR=Bedrock and rubble	7.8
D=Dredge spoils	0.7
RS=Rubble and sand	5.4
S=Sand	21.1
Total	35.0

Figure 6. Surficial substrates and bathymetry of a reef in Lake Huron. Water depths are in meters.

describes studies underway in which the system was able to not only define sea grass beds, but also to distinguish between four different foliage or growth states—new growth, mature, dying, and dead.

The sampling power and accuracy of RA are high. Under some conditions RA can produce good data while the survey vessel is operating at speeds >38 km/h. The manufacturer offers a self-contained system that includes a 150-kHz RA that is has a beam angle of 20 degree and is designed for use in water 1–5m deep. The most accurate data are produced with survey-grade echo-sounders with narrower beam angles. The RA processor interfaces with the newest differential GPS (DGPS) systems to allow positioning within 1 m or less.

RoxAnn was used for more than 60 days in 1995–1996 to survey and map surficial substrates and bathymetry between the 5- and 35-m depth contours along 225 km of Minnesota's rugged and frequently stormy Lake Superior shoreline. The RA system, which included a survey-grade echo-sounder with an 8 degrees beam angle, produced the data for the computer-drawn substrate and bathmetric map shown in figure 8.

Preliminary processing of these RA data suggest excellent results in identifying and delineating substrate types and recording bathmetry. The system also provided some interesting information on habitats of benthic biota, discriminating between sand substrates with freshwater mussel siphon holes and those without. Although performance was generally excellent, significant degradation of the data occurred when the vessel was turning at the end of each transect, and when sea height exceed about 0.6 m. Survey speeds >21 km/h increased cavitation effects on the transducer and produced poor data. Higher survey speeds could have been achieved with a thru-hull or acoustically transparent window mounting of the echosounder transducer.

Electronic "noise" from the vessel engines and marine electronics adversely affected the RA, DGPS, and computer monitor. A clean power source provided by the Heart Interface Freedom 20 inverter/charger solved most of these prob-

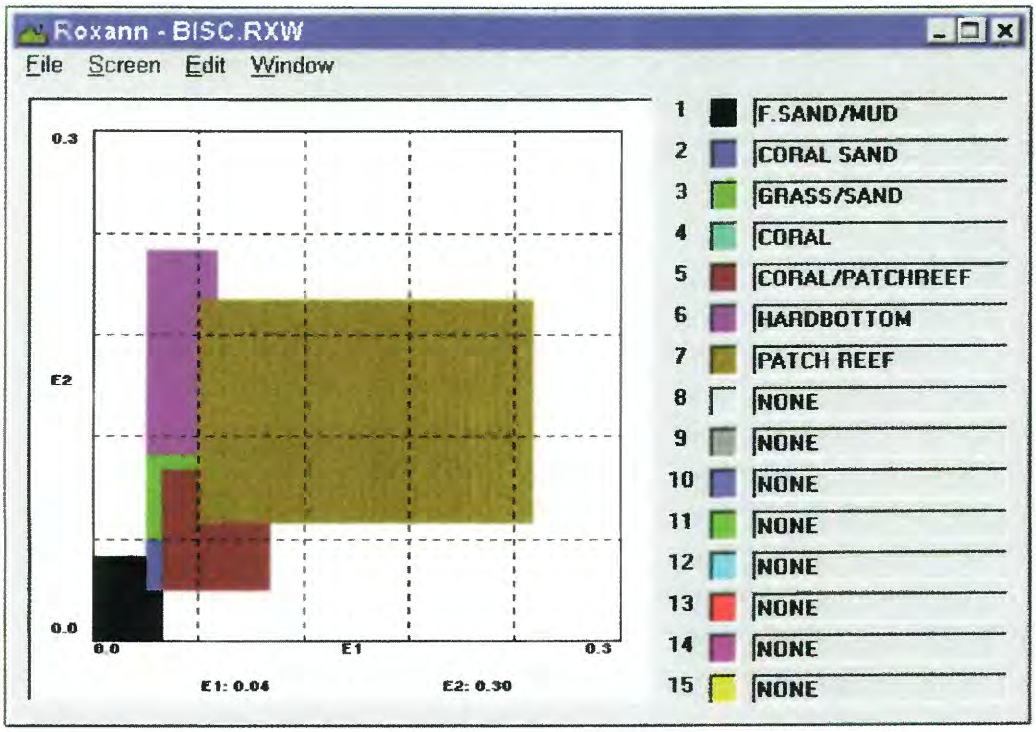


Figure 7. The RoxAnn square or color box displayed on a color monitor with Hypack for Windows software. The E1 values provide a numerical index of substrate roughness and the E2 values show hardness. In this example the system has been programmed to identify seven different substrate types ranging from fine sand and mud to patch reef.

lems. A hull-mounted plate installed for grounding of all RA system components separately from those of the engine(s) and marine electronics is recommended to help eliminate electronic noise on vessels with nonmetallic hulls.

Signal degradation also occurred on steeply sloping bottoms and when the substrate changed abruptly from soft to hard. Reducing vessel speed improved the signal in these situations. For areas with mostly hard substrates, a lower gain setting for the RA improved the data. However, changes in the gain also shift the RA E1 and E2 data values and require recalibration and ground truthing of the substrates. Before beginning a survey it is best to select a gain setting that will match the substrates that are expected to be encountered. A lower setting is best for hard substrates, medium for mixed, and high for soft.

Calibration and ground truthing of substrates is a time-consuming and exacting process that requires careful attention to detail. Changing the transducer unit (e.g., for repairs) will require recalibration and ground truthing of substrates. Changing the echosounder make or model requires recalibration of the RA at the factory in Scotland.

The RA Seabed Classification System used in the Lake Superior survey described above included the following components: RoxAnn ; Interspace 448 Echosounder (hydrographic quality—meets IHO standards); Leica DGPS receiver and high performance antenna; Sea PC computer (waterproof, shock mounted, pentium 166MHZ, 16Mb ram, 1.6 Gb hard drive, 1.44 Mb diskette drive, 4 serial comports, color monitor, watertight keyboard /pointing device); Hypack for Windows hydrographic surveying software; and Heart Interface Freedom 20 inverter/charger system. The total cost of the system was about $57,000. An Amphico drop video system ($15,000) was used to provide ground truth.

Acoustic Doppler Current Profiler

The ADCP uses multibeam hydroacoustic technology to measure water velocity and water depth by measuring the Doppler effect. Compact systems are available specifically for shipboard use in large rivers. The basic system from one manufacturer, RD Instruments (RDI), includes transducer-receivers designed for over-the-side use or for in-hull installation and a deckbox, which supplies power to and communicates with the unit. Some deck boxes are furnished with an internal battery and others are equipped with AC converters. A laptop or other portable PC is required to collect and display the data.

The principles of operation are detailed in RDI (1989). A recent description of survey techniques and a quality assurance plan for using the system to make discharge measurements is given by Lipscomb (1995). Additional description and evaluation of system capabilities is provided by Admirral and Demissie (1995). Basically, the system transmits sound bursts into the water and particles in the water (e.g., plankton) reflect some of this sound energy back to the transducer-receiver. The system uses this reflected energy to create a vertical profile of the water column containing up to 128 cells. Motion of the particles in each cell is read by the system as a Doppler shift and translated into an average current velocity measurement for the cell.

The RDI system is operated with vendor-supplied software that allows the user to collect data at intervals tailored for the specific application. Cell length, the number of cells, and the number of water and bottom measurements per ensemble are among the instructions that can be specified by the operator to ensure that the data collected adequately represent the survey site. As the survey vessel crosses the river channel, the system records the current velocity for each of the cells. These data are displayed graphically in real time on the PC video screen in one of several operator-selected outputs. The system software also automatically calculates river discharge across the transect.

The RDI system was used for a current velocity survey in the North Channel of the St. Clair River, Michigan in August 1996. In this application, depth cell length was 40 cm, the number of cells was 40, and an ensemble consisted of five water and four bottom measurements. These instructions permitted sampling to a maximum depth of 55.4 ft (16.9 m) and an ensemble to be computed every 2.5 s. The transect was located at about the middle of the reach shown in figure 4 . It was run on a course of about 0 degree, from the south shore, where the river bed was gently sloping, to the more steeply

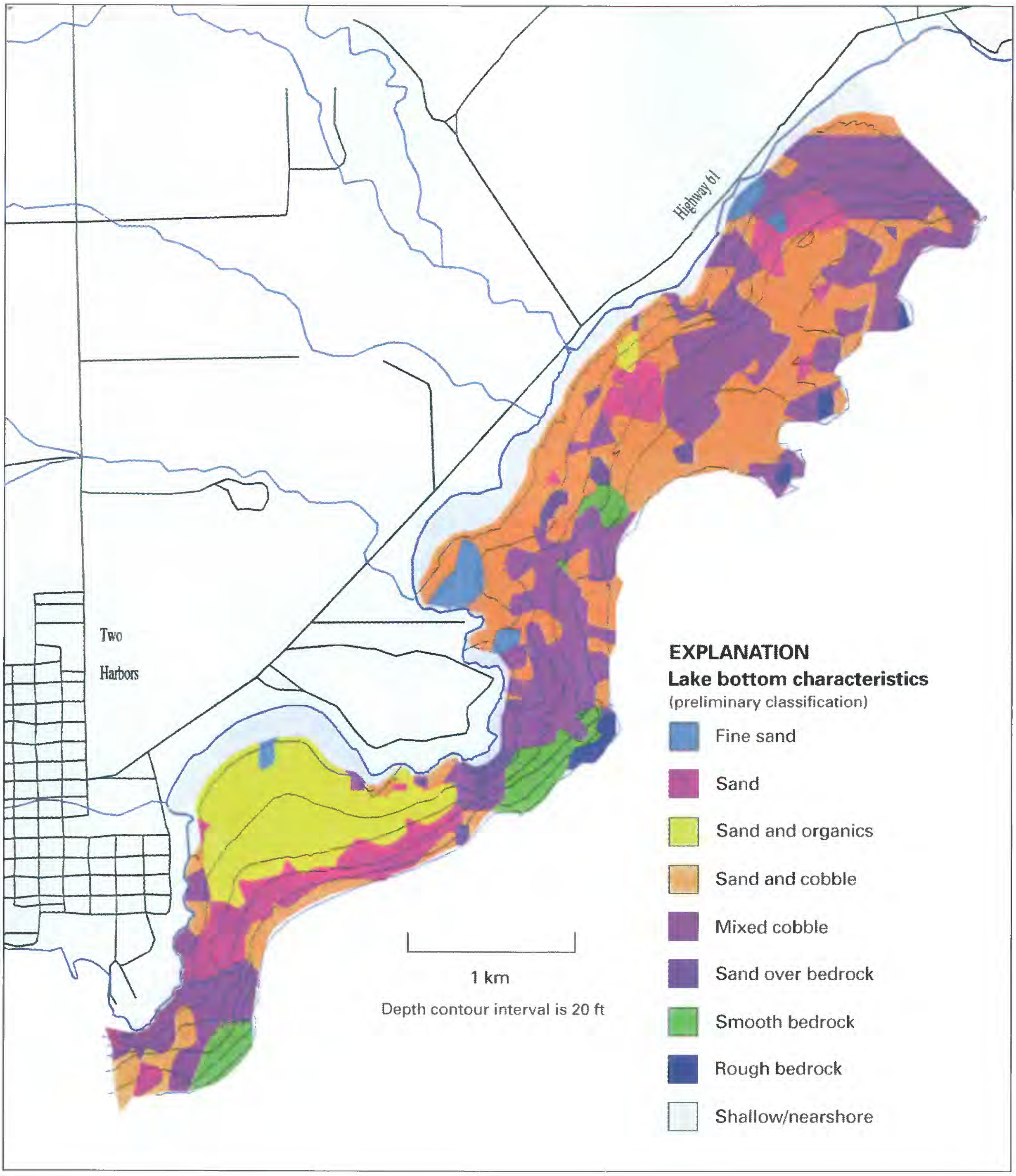


Figure 8. Computer-drawn map produced from RoxAnn survey data for the lake bed along a portion of Minnesota's shoreline of Lake Superior. Data from Natural Recoures Research Institute, University of Minnesota–Duluth.

sloping, bulkheaded, north shore. This measurement included 55 ensembles and indicated a discharge of 67,700 ft/s (20, 635 m/s). Figure 9 is an example of one display option that uses a colored block to represent velocity of an individual cell. This display indicates that nearshore velocities were 0.8–1.0 ft/s (0.2–0.3 m/s) and that most of the flow was in the thalweg where velocities were 1.0–1.2 ft/s (0.3–0.4 m/s).

A complete, direct reading, broadband ADCP system costs about $50,000–55,000.

Remotely Operated Underwater Camera Systems

A wide variety of remotely operated underwater camera systems are now available for use in large rivers. These systems are compact and portable and can be easily used to describe the physical environment, provide ground truth information for SSS and RA surveys, and make microhabitat observations for species of interest. Most systems employ video cameras because they operate in real time, have good resolution, can produce black and white or color images, and can operate at extremely low levels of ambient light. Artificial lights are usually incorporated into systems that are designed for use at night or in deep water. These camera systems are basically designed to operate primarily in one of three modes: drop, towed, or self-propelled.

Drop-camera systems are typically small and inexpensive. The camera is generally fixed rigidly within a frame that is raised and lowered vertically to position the camera so that it will be properly focused to view a small (ca. 1 m^2) area of bottom. The water column can also be viewed during descent and ascent or in stationary mode at any depth of interest. The camera images are displayed on shipboard and can be taped and stored.

Towed systems are typically more expensive and versatile than drop cameras; they usually can be used both in the towed and drop modes. One such system, the TOV-1 (figure 10), employs a remotely operated camera that includes, as a basic package, a high-resolution, low light (4 lux), black and white camera with an 8-mm, wide-angle (40 degree) lense. The camera is mounted at a downward viewing angle, which permits both straight ahead and downward viewing. The TOV-1 is deployed on a 46-m umbilical. Auxiliary lighting includes two 100-w tungsten halogen lamps attached to the unit. The camera images are displayed in real time on any standard shipboard video monitor. The shipboard monitor is not included in the basic package. A standard VCR can be added to the shipboard system to provide a permanent record of the camera images. The TOV-1 is towed by its umbilical and is stabile at water velocities to about 18 km/h. Operating depth is controlled by the amount of umbilical that is released and the towing speed. Other optional features include additional auxiliary lighting, a color video camera, a longer umbilical, and a 150-m depth operating capability.

Self-propelled systems are the most expensive and versatile. The Benthos, Inc. Mini-Rover MK II (figure 11) is an example of one of the smaller, self-propelled ROVS that are suitable for use in portions of large rivers where current velocities are low. This vehicle is equipped with a high-resolution, low-light, color video camera that relays video images through an umbilical to the shipboard video monitor. The video screen also shows the MK II operating depth, compass heading, and the altitude above or below a preset operating depth. The video screen images are recorded on tape for later analysis and archiving. The MK II is maneuvered with vertical and horizontal thrusters that are controlled with joysticks by a shipboard operator. The MK II has a maximum operating depth of about 300 m and a maximum forward speed of about 4–5 km/h. The MK II is usually operated by paying out the umbilical and using the thrusters to control its position. However, in deeper water, when the current velocity exceeds 1–2 km/h, it is usually necessary to attach the Mk II to a 15 kg "downweight" that can be raised and lowered on a cable with the MK II. This downweight facilitates spot placement of the MK II on the bottom and also helps it hold position. In these circumstances, and especially at higher current velocities, the MK II is essentially operating as a drop or towed camera. Thus, for work in large rivers where the current velocity typically exceeds 1–2 km/h, the towed ROV systems probably have greater utility than the MK II or similar self-propelled ROVs.

Despite its limitations in flowing water systems, we operated the MK II on a downweight in the North Channel of the St. Clair River in July 1996. In the reach of the river shown in figure 4, we recorded excellent images of the river bed; several species of native fish, including smallmouth bass (*Micropterus dolomieu*), rock bass (*Ambloplites rupestris*); and exotic biota, including zebra mussels (*Dreissena polymorpha*) and gobies (*Neogobious* or *Proterorhinus* spp.). Photographs like those in figure 12, which were made from the video screen images produced by the MK II, are usually of sufficient technical quality to permit them to be published in scientific journals. In addition to providing useful quantitative data on microhabitat distribution, the ROV can also be used to make direct counts and population estimates of fish (Edsall 1995; Edsall et al. 1993). Periphyton distribution can also be determined with the ROV or other underwater camera systems (Edsall et al., 1991).

Remotely operated camera systems vary widely in price. The MK II used in the St. Clair River survey described above retails for about $40,000, the TOV-1 for about $4,200, and the Lake Superior survey drop camera for about $15,000.

Geographic Positioning Systems

The GPS technology provides one of the simplest and most accurate ways to geo-reference habitat information. This technology has several advantages over other systems including: (1) portability—GPS's are relatively small, and are typically hand-held units, (2) simplicity—a GPS is typically self-contained, requiring little or no complicated equipment setup, (3) reliability—the GPS system is world-wide, 24-h/day coverage, and is not affected by many of the environmental factors that plague some of the other systems such as Loran-C, and (4) accuracy— many GPS's are capable of differential correction which yields positional accuracies of < 5 m, and 20-cm accuracy is easily obtainable. The GPS units range widely in capability, accuracy, and cost. The simplest hand-held units that give location and simple navigation functions cost as little as $100. Extremely precise, survey-grade units that may simultaneously collect and process other data and store these data for direct downloading into a GPS can cost as much as $30,000.

The GPS system consists of a receiver and a group of satellites orbiting the earth at high altitude. Calculation of the receiver's position is based on satellite "ranging." Each satellite transmits a coded signal at a specific time interval. The receiver searches for the signal and then determines how long it takes for the signal from the satellite to reach the receiver. Once the GPS receiver calculates these "ranges" for four satellites, it can precisely determine its own, three-dimensional location in space. The GPS receiver recalculates these positions every second, and constantly searches for additional satellites to range to improve the accuracy of the receiver location information.

The GPS satellites transmit three coded signals: Course-acquisition (C-A), Precise code (P-code), and the Department of Defense encrypted code (Y-code). The C-A code is the simplest to receive, and can be picked up by all GPS receivers. The C-A code is also the least precise of the GPS signals. When receiving C-A code, the receiver's calculated position accuracy is generally no better than ±15 m CEP (Circular Error Probability roughly equal to 1 standard error). To add to this error, the Department of Defense intentionally alters the signal from the satellites— a process called Selective Availability (SA). The SA causes an individual position calculation to be in error by as much 100 m (Hurn, 1989). The P-code is more precise than the C-A code but is also much more difficult for the receiver to interpret. A much higher grade, more expensive receiver must be used to process the P-code signal. When properly used, P-code receivers, can achieve position accuracies in the 1-5 m CEP range. The P-code is also subject to SA which can greatly degrade an individual receiver's positional accuracy. The encrypted Y-code is essentially the P-code which has been encrypted to protect the signal from being used by "unauthorized or hostile" users. Standard GPS receivers, including P-code receivers, cannot interpret or process this signal without a special "key" to unlock the overriding encryption. A receiver that contains the Department of Defense key and receives the Y-code signal can achieve position accuracies in the 2-5 m range. The Y-code is not subject to the effects of SA.

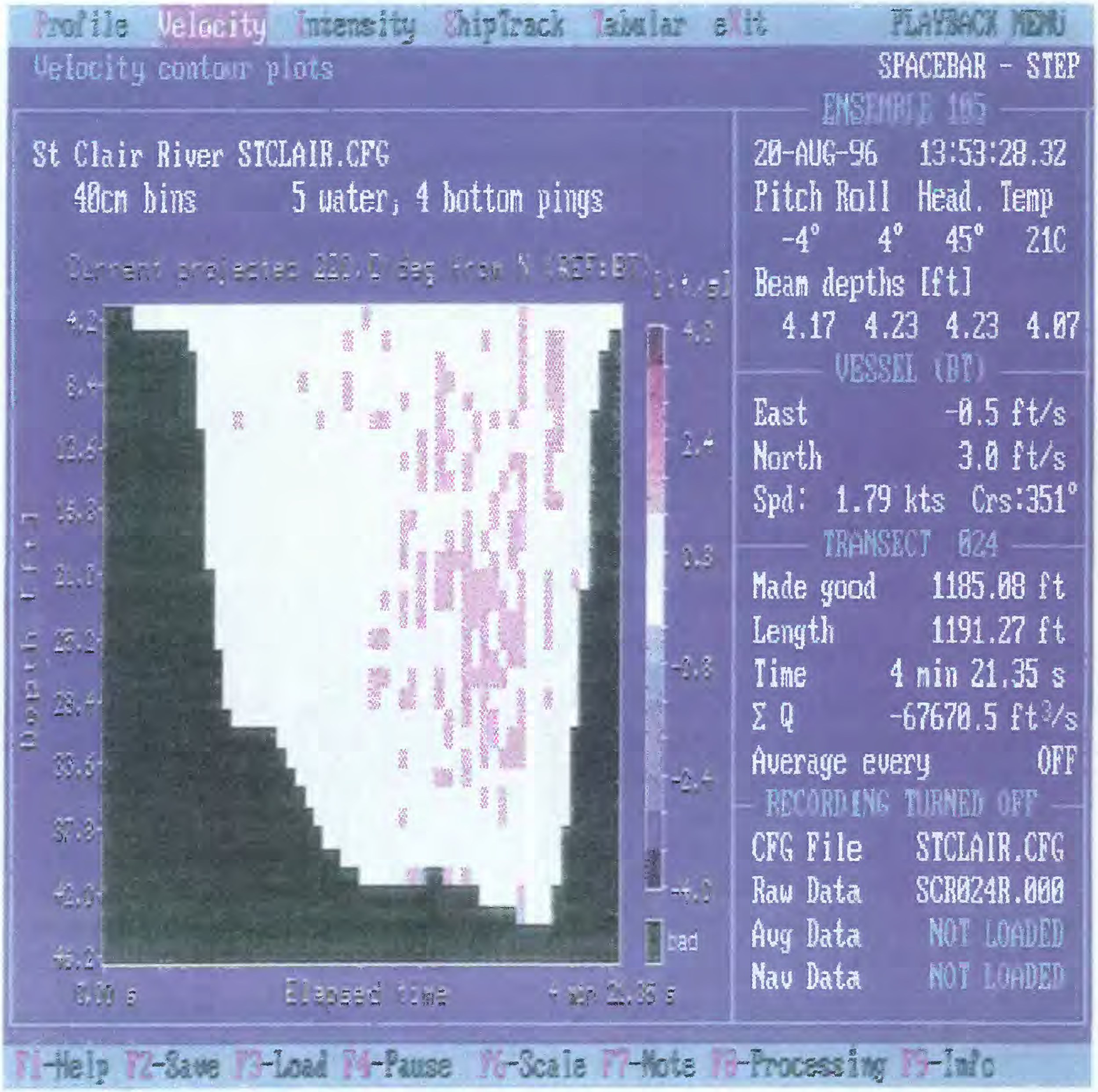


Figure 9. Computer screen output from the acoustic Doppler current profiler used in the North Channel of the St. Clair River, Michigan in July 1996

To offset the effects of SA on standard C-A code and P-code receivers, a process called "differential correction" can be implemented. Differential correction involves a second, stationary receiver (commonly known as the base station) in which the position of the antenna is precisely known (i.e., within 2–5 cm), and is within 300 miles from the user's receiver (commonly known as the rover). The base station collects the signals from the satellites, compares the satellite calculated position to the known position, and processes offsets for these satellites to "correct" the errors in the signal. These offsets can then be applied to the rover's calculated positions to correct the errors in that receiver. Differential correction can improve position accuracy of a C-A receiver to 1–3 m, and a P-code receiver to < 1 m (Deckert and Bolstad, 1996). Depending on the "grade" of the receiver, differential correction of a P-code receiver can achieve about ±1 cm accuracy. Differential correction can be used with the Y-code receivers.

However, differential correction mainly corrects for effects of SA, which does not affect the Y-code signal; as a result, the improvement in position accuracy is not as dramatic with Y-code receivers. Improvement of Y-code receivers using differential correction generally reduce error to about ± 1 m.

Differential correction can be applied to the rover unit in post-processed or real-time modes. For post-processed differential correction (DGPS), the GPS positions can be collected in the field and stored in the GPS unit; the offsets are then applied at a later time in a computer using specific GPS correction software. This is the least costly way to collect DGPS positions. Real-time differential correction (R-DGPS) is considerably more complex than post-processed DGPS. With R-DGPS, a "link" must be made between the base station and the rover unit so that the offsets calculated by the base station can be applied in real time to the current receiver position. This link is typically made by radio from a base station that usually must be within 100 miles of the rover. The rover must also have a radio receiver to hear the base station updates. This considerably increases the cost and complexity of the R-DGPS system. An alternative to the radio link has been implemented by the U.S. Coast Guard, which maintains a series of R-DGPS navigation beacons. These navigation beacons are GPS base stations that are coupled with encrypted radio transmitters, and are being operated on most of the navigable waterways in the United States (Van Diggelen, 1995). For a minimal investment, the rover can be fitted with a "chip" and radio receiver that can receive and decode the navigation beacon offset data and provide R-DGPS. Many of the better marine GPS receivers come with the chip already built-in, and some also contain the radio receiver. Examples of situations in which R-DGPS would be necessary include direct input of GPS data into SSS during data collection for computer mosaicing, target analysis, and image processing, and revisiting a previously surveyed site in which DGPS positions had been collected.

Much of the remote-sensing equipment being used has the capability to link directly with the GPS unit thereby receive continuous updates of location and navigation. These spatial data can be used by the remote-sensing processing software to correctly position the remotely sensed data. A GPS unit suitable for use in remote-sensing habitat surveys would minimally be one that is capable of collecting GPS data for post-

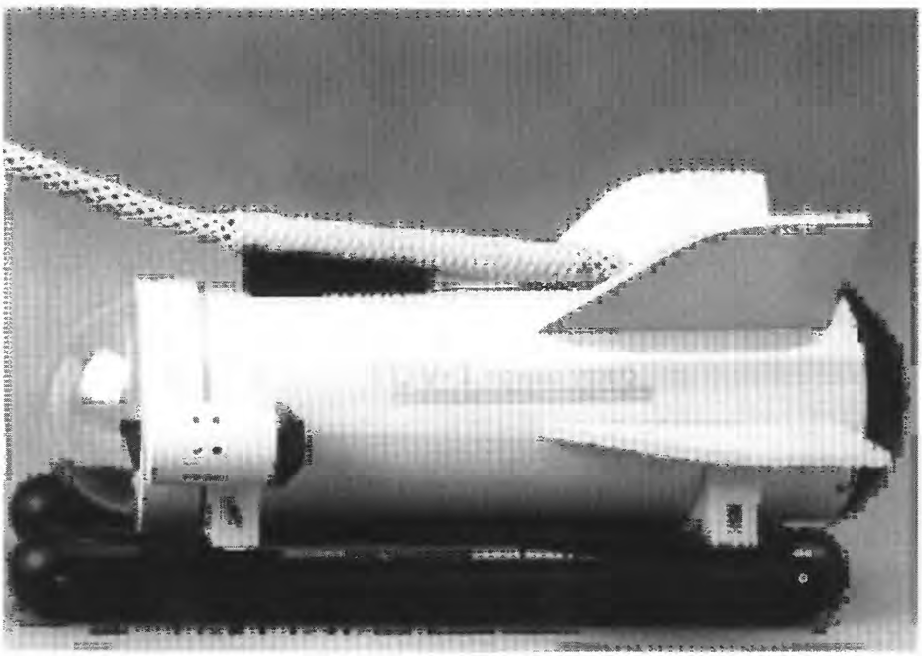


Figure 10. The TOV-1 is an example of an inexpensive, towed camera system that can be used in both the towed and drop modes. The TOV-1 is towed by its umbilical and is stable over the range of water velocities found in most large river systems.

processed DGPS. Most GPS units capable of DGPS usually have the designation “mapping grade” and can collect and store many other forms of data and download these data directly into some form of GIS. For direct input of GPS positional data into another sampling device such as SSS or ACDP, it is recommended that the GPS unit be capable of operating in R-DGPS to supply the device with the most accurate positional data in real-time. This will allow the best possible processing of the remotely sensed data by that device. Because the accuracy of a GPS receiver operating in R-DGPS mode can vary from ±3 m to ±1 cm, the spatial resolution of the project (i.e., the size of the smallest area to be delineated) will determine the amount of investment involved for the GPS. An inexpensive alternative for Federal Government employees is the Precise Lightweight GPS Receiver (PLGR; Rockwell International 1996). The PLGR, which was developed for the Department of Defense for use in military situations, has recently been made available for use by other Federal Government agencies. The PLGR uses the encrypted Y-code, which can attain positional accuracies of 2–5 m in real-time without the use of DGPS. Because the encryption key is considered “sensitive” and has national security implications, use of a PLGR with an active key is limited to official use by Federal Government personnel. The Great Lakes Science Center presently uses a PLGR for GPS input into their SSS. Repeatability of a previous site using the PLGR is an order of magnitude better (2–5 m) than that provided by Loran-C navigation (±33 m) as the primary navigation source. The 2–5-m level of accuracy is adequate processing data

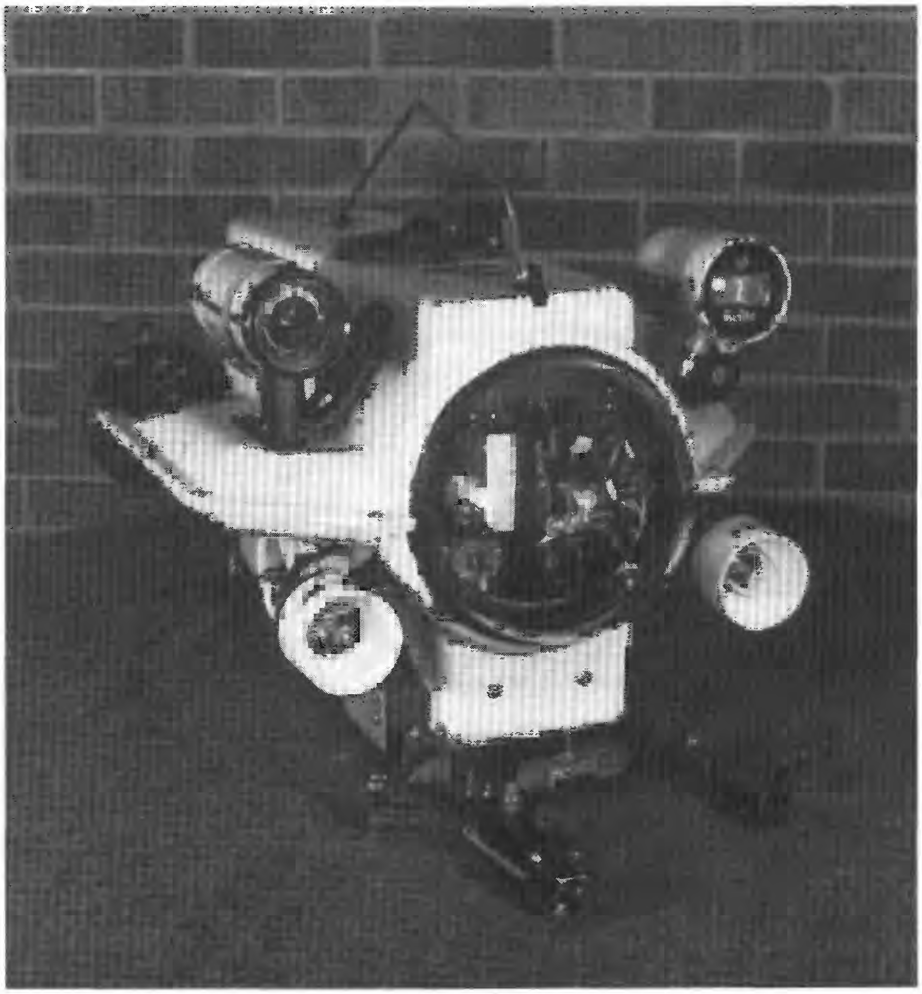


Figure 11. The MK II Mini-Rover. The shipboard components of the system include a shipboard video monitor, tape recorder, and joystick controls that are used to maneuver the MK II.

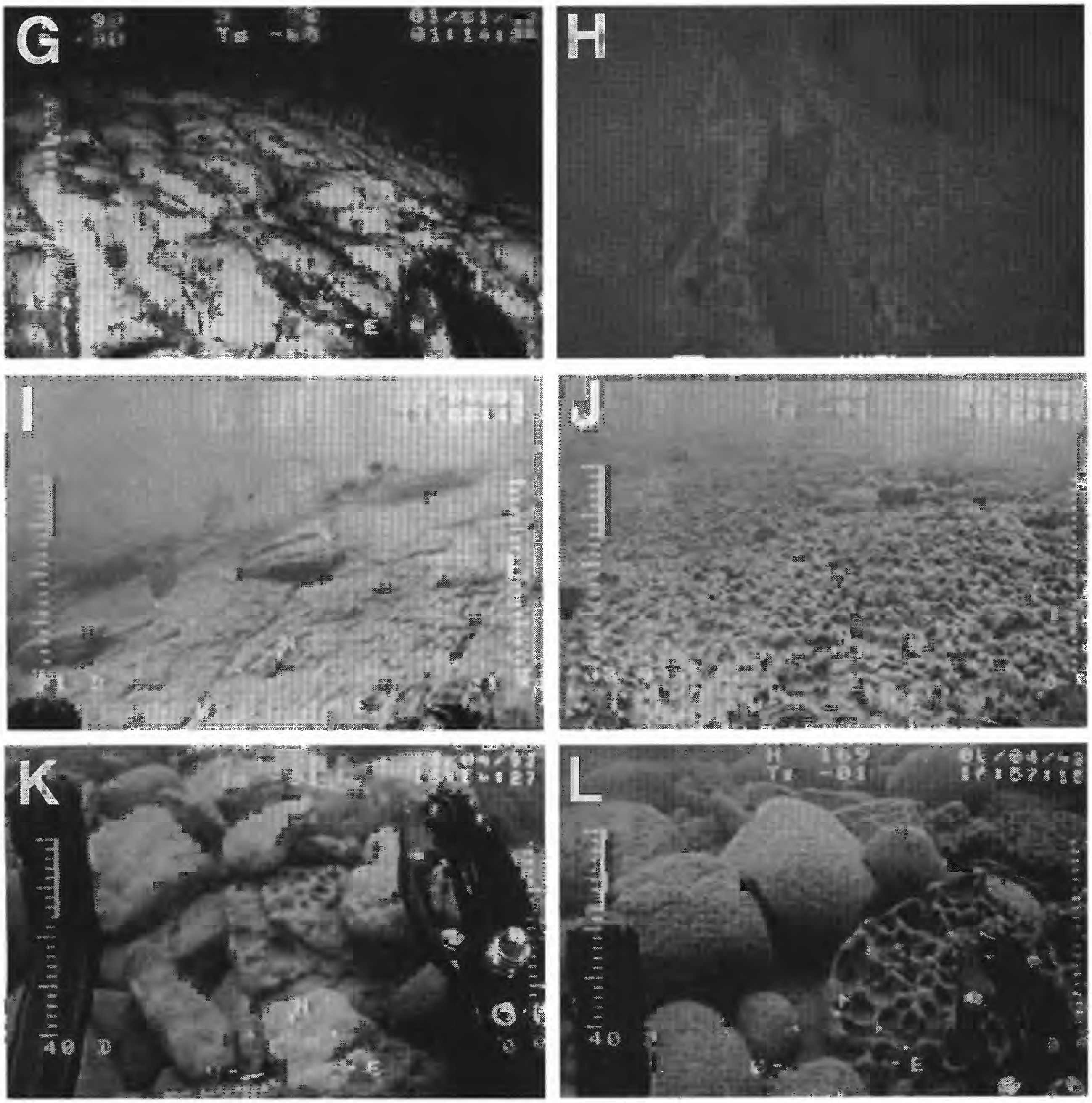


Figure 12. Photographs made from video screen images produced by the MK II Mini-Rover video camera in Lake Huron. The skids of the MK II , which can be seen resting on the bottom in panels K and L, are about 15 cm apart.

collected with a basic SSS system. However, a R-DGPS system capable of 20-cm accuracy would be required to fully exploit the processing and internal mosaicing capability of the software capabilities of a system such as the Midas SSS. The cost for a PLGR is about $1,600 whereas the R-DGPS system that uses the U.S. Coast Guard navigation beacons costs about $6,000.

Laser Level Survey System

The ACDP provides accurate distance measurements (reach and transect length), as well as channel bed surface profiles. When used together, the ACDP and GPS provide the channel bed surface profiles with real-time geo-positioning. One weakness of the GPS is that elevation data is only accurate to within 4.5 m. To counter this weakness, a LLSS could be used to obtain the necessary elevation measurements. The leading LLSS is the Nikon, TOP GUN A-Series Total Stations (Nikon, 1996). The TOP GUN system contains many useful features that would improve habitat elevation data collection and provide secondary reach and transect distance measurements for quality assurance to the ADCP and GPS distance measurements. The TOP GUN uses an infrared electronic measuring device that can measure distances up to 3,600 m under good conditions; this extended measurement range would be valuable in minimizing the number of turning points surveyed and number of times needed to cross the river in the boat to save time in the field. One of the more important components of the system is its full computer compatibility (RS-232C interface). The system automatically and quickly (0.5 s) measures distances and angles and then does the trigonometric calculations to give accurate distance and elevation figures. The system also will automatically calculate elevation and distance differences between two points and then display the results on the screen. This option permits rapid and accurate measurement of distance and elevation, as needed to document reach and transect length, bank height, floodplain distances, and other such physical dimensions of the study site that are required for habitat characterization.

CAVEATS AND GENERAL RECOMMENDATIONS

1. The specific systems we describe here are necessarily only a few of the many that are available on the market. Prices vary widely among systems and suppliers, and new systems are appearing frequently. Industry magazines such as *Ocean News and Sea Technology* describe state-of-the-art underwater camera and side-scan sonar systems and current price information. Other industry publications and information sources are identified in the present document. Because some of the technologies are evolving rapidly, and costs can also change rapidly, we recommend that industry sources be consulted before developing a large river sampling protocol involving the use of a specific remote-sensing technology.

2. The newer remote-sensing systems are becoming more user-friendly, but also more sophisticated, and most of those that we describe here require some formal training before they can be used effectively. Training in the maintenance of these systems is also recommended. Some ROVs, for example, require regular internal cleaning to remove debris that can affect maneuverability and damage the propulsion units.

3. Some of these systems are quite portable and do not require calibration and ground truthing when moved to a new site or used with a different vessel, whereas others, such as the RA, may require careful on-site adjustment to perform effectively.

4. For the above reasons, and to promote a more cost-effective approach to the characterization of physical habitat in large rivers, we recommend that consideration be given to developing regional technical service units that would own and operate the more expensive and sophisticated systems (e.g., RA, SSS, ADCP, and some GPS units) needed to perform the remote-sensing surveys and to provide the information needed to support NAWQA field sampling programs.

SPECIFIC RECOMMENDATIONS

This portion of the report makes specific recommendations for the use of remote-sensing approaches for collecting habitat chacterization data required in large rivers and in non-wadeable portions of medium-sized streams and rivers. The major section headings used here follow those in Meador et al. (1993).

Reach Characterization

Selecting a Stream Reach

We strongly recommend a remote-sensing reconnaissance survey be performed to select the stream reach for study. For reasons outlined above, it is difficult or impossible to adequately visualize the habitat characteristics of large river reach simply by looking at the surface of the water, the shallow littoral areas, and the terrestrial setting. The reconnaissance survey should be a scaled-back version of the fixed-site habitat characterization survey (see below), but should be performed in such a way that the information collected will help complete the required habitat characterization survey of the reach, if the reach is ultimately chosen for study.

A. Fixed Sites

1. First-level reach characterization

Recording—Use the Reach Characterization Form given in Meador et al. (1993); complete the form using information from the remote-sensing applications. Supplement the form with the remotely sensed data and numerical and graphic data compilations performed with the equipment and GIS technology. Develop standardized GIS display formats for the remotely sensed data.

Distances, locations, boundaries, elevations—Use GPS and a laser level survey system (LLSS) as tools for recording distance, the location of features of interest, and the boundaries of geomorphic channel units, and for determining elevations.

Depth, bed substrate, and embededness—Use SSS, RA, and a ROV to survey on cross-channel transects; extract data from these records for three points along each transect and record on the form as stipulated in the manual[2]. Habitat features—Extract information from remotely sensed data and record on the form. Add information from visual inspection performed in shallow littoral areas where remotely sensed data not collected. Diagrammatic mapping—Rely principally on remotely sensed data and electronic and machine hard-copy data output. Annotate this output manually as needed.

2. Second-level reach characterization

Channel bed and water-surface profile —Use bathymetric data collected by SSS, RA, or ADCP to develop channel bed profile; use LLSS to develop surface water profile. Current profile—Use ACDP to collect current data. Extract data and record on form of choice so it can be compared directly with manually collected data from small and medium-sized streams and rivers[2]. Channel substrate particle size—Use SSS, ROV, and RA data to describe substrate particle size distribution. Reach map—Construct reach map from remotely sensed data.

B. Synoptic sites

Procedures—Adopt manual and remote-sensing habitat characterization procedures used for fixed sites.

Microhabitat characterization

Procedures—Use manual and remote-sensing habitat characterization procedures used for fixed sites. Adapt as needed.

[2] This approach will facilitate comparison with small-stream and medium-stream and river data sets, which are based on data that are manually collected.

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