96-53

Environment Canada
Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau
Environnement Canada

Preliminary Results of Demonstration Capping Project in Hamilton Harbour

By:
A.J. Zeman & T.S. Patterson

NWRI Contribution # 96-53

96-53

MANAGEMENT PERSPECTIVE

Large volumes of contaminated fine-grained sediments represent a major cleanup challenge in the Great Lakes Areas of Concern. Subaqueous in-situ capping is a remediation technique in which contaminated sediments are permanently covered with a clean sediment cap, thus removing them from the overlying water column and biota. A capping demonstration project has been incorporated into the remediation strategy for contaminated sediments in the Harbour, prepared by the Technical Committee of the Hamilton Harbour Remedial Action Plan.

The capping one-hectare (100 m x 100 m) demonstration site is located in the water depth of about 15 m, which is a relatively low-energy environment with little potential for erosion of the cap due to waves and currents. Placement of a sand cap over very soft contaminated sediments occurred in the summer of 1995. The site was covered with 6,600 tonnes of clean sand using a multiple tremie tube system attached to a feed hopper mounted on a sand barge. A very accurate differential global positioning system was used. Comparison of pre-capping and post-capping echo sounding surveys showed even placement of the cap within the designated site boundaries, with some drifting of finer sand fraction outside of the site boundaries. The actual thickness of the cap (about 34 cm average) is expected to be fully effective in preventing any contaminant migration through the cap. Following the cap placement, metal profiles measured on sediments cores are comparable to pre-capping profiles, with background concentrations measured in the sand cap. The PAH and PCB concentration profiles likewise show sharp breaks between the low concentrations in the cap and substantially higher concentrations in the underlying sediment.

The project has been sponsored by the Great Lakes 2000 Cleanup Fund of Environment Canada, and it is a joint National Water Research Institute and Environment Canada - Ontario Region initiative.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Les grandes quantités de sédiments fins contaminés dans les secteurs préoccupants des Grands Lacs soulèvent un défi de taille. Le recouvrement subaquatique in-situ est une technique d'assainissement dans laquelle les sédiments contaminés sont recouverts, de façon permanente, de sédiments propres afin de les séparer de la colonne d'eau et du biote sus-jacents. Un projet de démonstration de cette technique fait partie de la stratégie d'assainissement des sédiments contaminés du port de Hamilton, préparée par le Comité technique du Plan d'assainissement du port de Hamilton.

Le site de démonstration de 1 ha (100 m x 100 m) se trouve à une profondeur d'eau de 15 m environ, milieu relativement calme où les vagues et les courants risquent peu d'éroder la couverture de sable. La mise en place de la couverture sur des sédiments contaminés très mous a été réalisée à l'été 1995. On a recouvert le site de 6 600 tonnes de sable propre à l'aide d'un système à tubes multiples monté sur la trémie d'alimentation d'une barge à sable. Un système de positionnement global différentiel (DGPS) très précis a été utilisé. La comparaison des résultats des échosondages effectués avant et après le recouvrement a montré un étalement assez égal de la couverture à l'intérieur des limites du site désigné. Elles ont également indiqué que la fraction des particules fines de sable a quelque peu dévié vers l'extérieur des limites du site. On prévoit que l'épaisseur actuelle de la couverture (environ 34 cm en moyenne) sera tout à fait efficace et que les contaminants ne pourront pas la traverser. Les profils de concentration des métaux dans les carottes de sédiments prélevés après la mise en place de la couverture sont semblables à ceux observés avant le recouvrement; dans la couverture de sable, les concentrations correspondent aux niveaux ambiants. On a également noté de grands écarts entre les concentrations des HAP et des PCB dans la couverture et dans les sédiments sous-jacents. Dans les deux cas, les concentrations dans les sédiments étaient beaucoup plus élevées que dans la couverture.

Le présent projet, financé par le Fonds d'assainissement du programme Grands Lacs 2000 d'Environnement Canada, est une initiative concertée de l'Institut national de recherche sur les eaux et d'Environnement Canada - Région de l'Ontario.

ABSTACT

Placement of a pilot-scale one ha. sand cap over fine-grained contaminated sediments occurred in Hamilton Harbour, Lake Ontario, Canada in the summer of 1995. The site was covered with 6,600 tonnes of clean sand, to an average thickness of 34 cm. Adequate sand placement accuracy was possible up to wind speeds of about 30 km/h. Ultimate settlement of sediment due to primary consolidation was measured to ranged between 6 and 8 cm. Suspended material found in the water column during cap placement was almost entirely composed of fines associated with the cap sand. Core samples showed a sharp interface between the sand cap and sediments with no signs of extensive mixing. Based on data collected at this site, the sand cap was successfully placed in the designated area without any significant sediment disturbance.

Following the cap placement, metal profiles measured on sediment cores are comparable to pre-capping profiles, with background concentrations measured in the sand cap. The PAH and PCB concentration profiles likewise show sharp beaks between the low chemical concentrations in the cap and the substantially higher concentrations in the sediment underlying the cap. Concentrations of trace elements and nutrients were measured throughout the year in sediment/cap pore water using in-situ dialysis membranes (peepers). The vertical profile of oxygen-sensitive species, such as Fe, Mn, and SO_4, showed anoxic conditions below the top 4 cm of capping material. The calculated fluxes show that under reducing conditions redox species are mobile and the upwardly diffusing elements are trapped in the oxic zone near capping-water interface.

RÉSUMÉ

Dans le cadre d'un projet-pilote, on a placé à l'été 1995 une couverture de sable de 1 ha sur des sédiments fins contaminés dans le port de Hamilton, sur le lac Ontario, au Canada. Le site a été recouvert de 6 600 tonnes de sable propre pour former une épaisseur moyenne de 34 cm. Les vents ne dépassant pas 30 km/h, la mise en place du sable a pu se faire de façon précise. Le tassement final des sédiments dû à la consolidation primaire variait de 6 à 8 cm. Les matériaux en suspension dans la colonne d'eau pendant la mise en place de la couverture étaient presque entièrement composés de particules fines associées au sable utilisé. Des échantillons prélevés par carottage ont révélé une interface nette entre la couverture de sable et les sédiments, sans signe de mélange important. Selon les données recueillies sur le site, la mise en place de la couverture de sable dans la zone désignée a été un succès et n'a pas perturbé les sédiments de façon appréciable.

Les profils de concentration des métaux dans les carottes de sédiments prélevés après la mise en place de la couverture sont semblables à ceux observés avant le recouvrement; dans la couverture de sable, les concentrations correspondent aux niveaux ambiants. On a également noté de grands écarts entre les concentrations des HAP et des PCB dans la couverture et dans les sédiments sous-jacents. Dans les deux cas, les concentrations dans les sédiments étaient beaucoup plus élevées que dans la couverture. Les concentrations des éléments traces et des nutriants ont été mesurées au cours de l'année dans l'eau interstitielle des sédiments et de la couverture au moyen de membranes de dialyse in-situ. Les profils verticaux des concentrations d'espèces sensibles à l'oxygène comme Fe, Mn et SO_4 ont révélé des conditions anoxiques au-dessous de la couche supérieure de 4 cm de la couverture. Les flux calculés ont indiqué que, dans des conditions réductrices, les espèces rédox sont mobiles, tandis que les éléments diffusant vers le haut restent emprisonnés dans la zone oxique, près de l'interface couverture-eau.

96-53

Water Qual. Res. J. Canada, 1997
Volume 32, No. 2, 439–452

Preliminary Results of Demonstration Capping Project in Hamilton Harbour

A.J. ZEMAN AND T.S. PATTERSON

Aquatic Ecosystem Restoration Branch, National Water Research Institute, Environment Canada, 867 Lakeshore Road, Burlington, Ontario L7R 4A6

Placement of a pilot-scale sand cap occurred in Hamilton Harbour between July 31 and September 20, 1995. The harbour site is at a location where contamination of the bottom sediments is of concern. One ha of contaminated fine-grained sediments was covered with 6,600 tonnes of clean sand to an average thickness of 30 cm. A very accurate positioning system was required and placement with adequate accuracy was possible up to wind speeds of about 30 km/h. Initial readings of settlement gauges taken in September 1995 show the ultimate settlement due to primary consolidation to range between 6 and 8 cm. Preliminary results indicate that the suspended material found in the water column during cap placement was almost entirely composed of fines associated with the cap sand. Vibracores showed a sharp interface between the sand cap and sediments with no signs of extensive mixing. Based on multibeam echo sounding results and other supporting data collected at the site, the sand cap was successfully placed in the designated area without any significant sediment disturbance. Some horizontal spreading of sand fines occurred beyond the site boundary.

Key words: Hamilton Harbour, in-situ capping, contaminated sediments, sediment remediation, sediment remediation technology, pore water monitoring

On a placé une couverture de sable à l'échelle pilote dans le port de Hamilton entre le 31 juillet et le 20 septembre 1995. Le port est un endroit où la contamination des sédiments de fond est préoccupante. On a recouvert 1 ha de sédiments fins contaminés avec 6 600 tonnes de sable propre, ce qui a donné une couche d'une épaisseur de 30 cm en moyenne. Un système de positionnement très précis était nécessaire; cette précision pouvait encore être obtenue avec des vents ne dépassant pas 30 km/h environ. Les premières lectures au tassomètre prises en septembre 1995 montrent que le tassement final dû à la consolidation primaire peut varier de 6 à 8 cm. Des résultats préliminaires indiquent que le matériau en suspension observé dans la colonne d'eau durant la mise en place de la couverture était presque entièrement composé de particules fines associées au sable utilisé. Des carottes, prélevées au carottier à vibrations, présentaient une interface nette entre la couverture de sable et les sédiments et aucun signe de mélange important n'a été noté. D'après les données d'échosondage multi-faisceaux et d'autres données d'appoint recueillies sur le site, la mise en place de la couverture de sable dans la zone désignée a été un succès et n'a pas perturbé les sédiments de façon appréciable. On a observé un certain étalement horizontal de fines particules de sable hors des limites du site.

Mots-clés : Port de Hamilton, recouvrement in situ, sédiments contaminés,

assainissement des sédiments, techniques d'assainissement des sédiments, surveillance de l'eau interstitielle

Introduction

Capping Concept and Site Conditions

Subaqueous in-situ capping is the placement of a clean sediment layer over contaminated sediments that are typically fine-grained and of very soft consistency. This cost-effective and versatile remedial method has been used in Japan, on the west coast of the United States, and in Europe (Zeman et al. 1992). Capping eliminates the need for a new storage site, remediating contaminated sediment, and reduces the potential for disturbance of the sediment within the water column. As a result, in-situ capping may be considered to be more inexpensive and environmentally sound than dredging, when properly designed and in suitable environments. Suitable sites for capping can be restricted due to wave and bottom currents, bathymetry, and ship traffic. Capping appears to be an appropriate technology for long-term remediation. Existing field and laboratory results, mainly from the projects carried out by the U.S. Army Corps of Engineers (Brannon et al. 1985; Sumeri et al. 1991), indicate no appreciable migration of contaminants even after one decade following the cap placement.

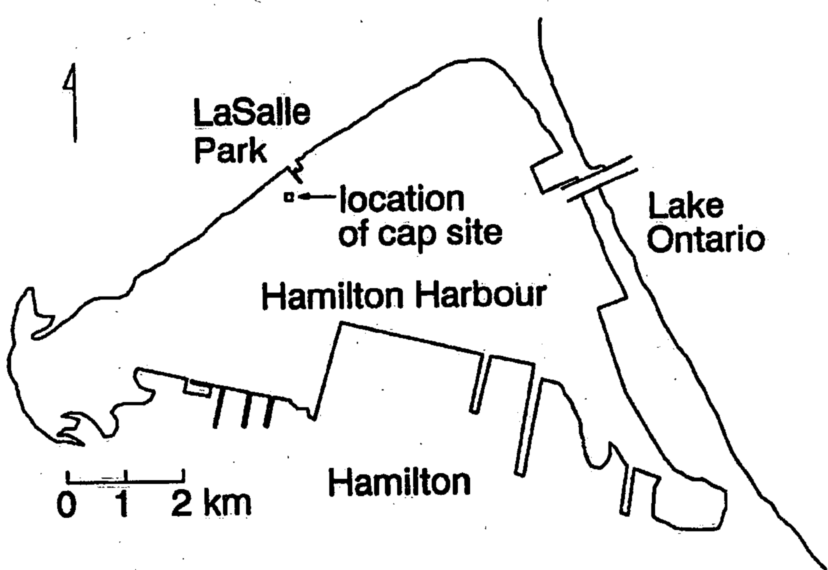

Fig. 1. Cap site location.

A pilot-scale sand cap was placed in Hamilton Harbour (Fig. 1) between July 31 and September 20, 1995. No other projects involving subaqueous capping have been documented at any scale in the Great Lakes region or in Canada. The selected site is at a location where contamination of bottom sediments is of concern. A substantial area of fine-grained sediments in the harbour exceeds the Ontario Ministry of Environment and Energy (MOEE 1994) sediment quality guidelines, at the severe effect level, for both metals and organic contaminants.

The demonstration site is located off the north shore of the harbour, 500 m south-west of LaSalle Park, measuring 100 x 100 m (Fig. 2). Water depths at the site range from about 12 to 17 m (International Great Lakes Datum 1985). Bottom sediments consist of about 30 cm of very soft black silty clay (contaminated from industrial sources) underlain by very soft greyish brown silt and clay (natural harbour sediments). The cap was placed with the intent to minimize sediment disturbance during capping operations. Detailed sedimentological, geotechnical, geochemical and biological conditions at the site were established through coring and baseline surveys in 1994 (Zeman et al. 1995). The site is in an area of high sediment toxicity, being above the severe effect level for several metals, whereas PCBs and PAHs are just above the no effect level.

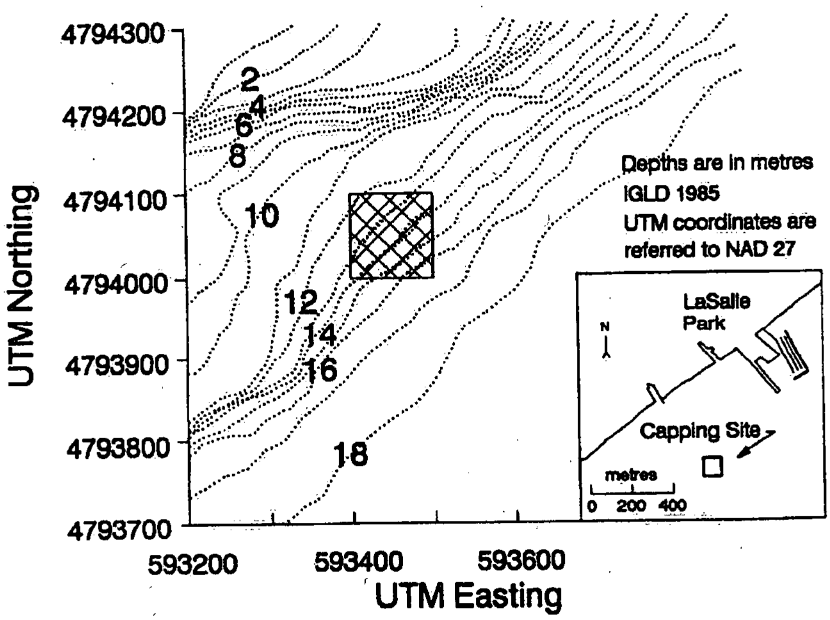

Fig. 2. Bathymetry in and around cap site.

Methodology

Placement Equipment

Anchors and cables

The controlled movement of the spreader barge during capping operations was based on a four-point mooring system. This involved the placement of four moors consisting of concrete block sets (five 1.5-tonne blocks in each set) on the harbour bottom, located approximately 30 m outside each corner of the demonstration site. A steel cable between the two west moors, and another cable between the two east moors, secured each winch barge (Fig. 3). Each cable was supported at the water surface by one of the two winch barges (approximately 6 m x 9 m) equipped with cable guides at each end, and a winch located at the centre of the barge. A third cable (the guide cable) was secured to the east and west winch barges. This guide cable was looped around the rotating capstan centrally located on the side of the spreader barge (Fig. 4). The winch moved the spreader barge along the guide cable.

Spreader barge and tugboats

The spreader barge used for the transport and application of sand could hold up to about 400 tonnes of sand. The barge had continuous metal walls around the perimeter for the containment of the sand.

Two tugboats were involved in the capping operations. The main tugboat (16 m x 5 m) was used to transport the spreader barge to and from the site, and to serve as a data collection centre for position and depth readings. During sand placement, the main tugboat was moored to the spreader barge. The smaller tugboat (11 m x 3 m) was used for north-south positioning control. The bow of the tugboat was tied to the broadside of the spreader barge in order to counteract the tendency for the barge to sway off its intended track line (Fig. 4).

Sand spreading system

The sand used for cap placement was placed on the spreader barge, which was moved to the site by a tugboat. Medium to coarse sand was used, with an average grain size diameter of 0.5 mm, and was obtained from a nearby sand pit. Approximately 6,600 tonnes of sand was used for applying the cap. A custom-designed hopper and tremie tube system distributed the sand.

A 3-m wide hopper fixed to the end of the barge distributed the sand through a series of twenty 130-mm dia. and approximately 12-m long tremie tubes (Fig. 5). A small front-end loader was used to transfer the sand from the pile to the hopper. A rotating, adjustable speed paddle was located at the base of the hopper to aid in the sand distribution. A generator driven pump supplied harbour water through the tremie tubes to prevent plugging or bridging of the sand. The paddle system was calibrated to deliver approximately 0.75 tonnes of sand per minute with an

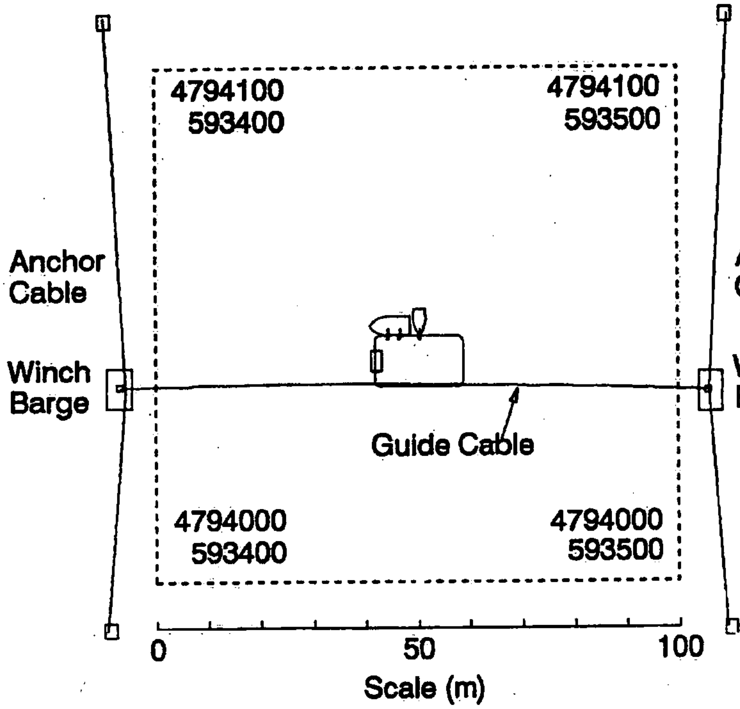

Fig. 3. Layout of placement equipment and cables.

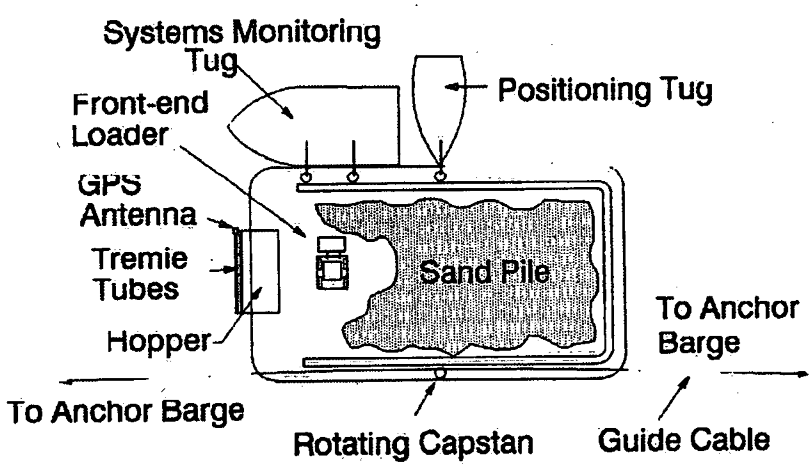

Fig. 4. Configuration of vessels for cap placement.

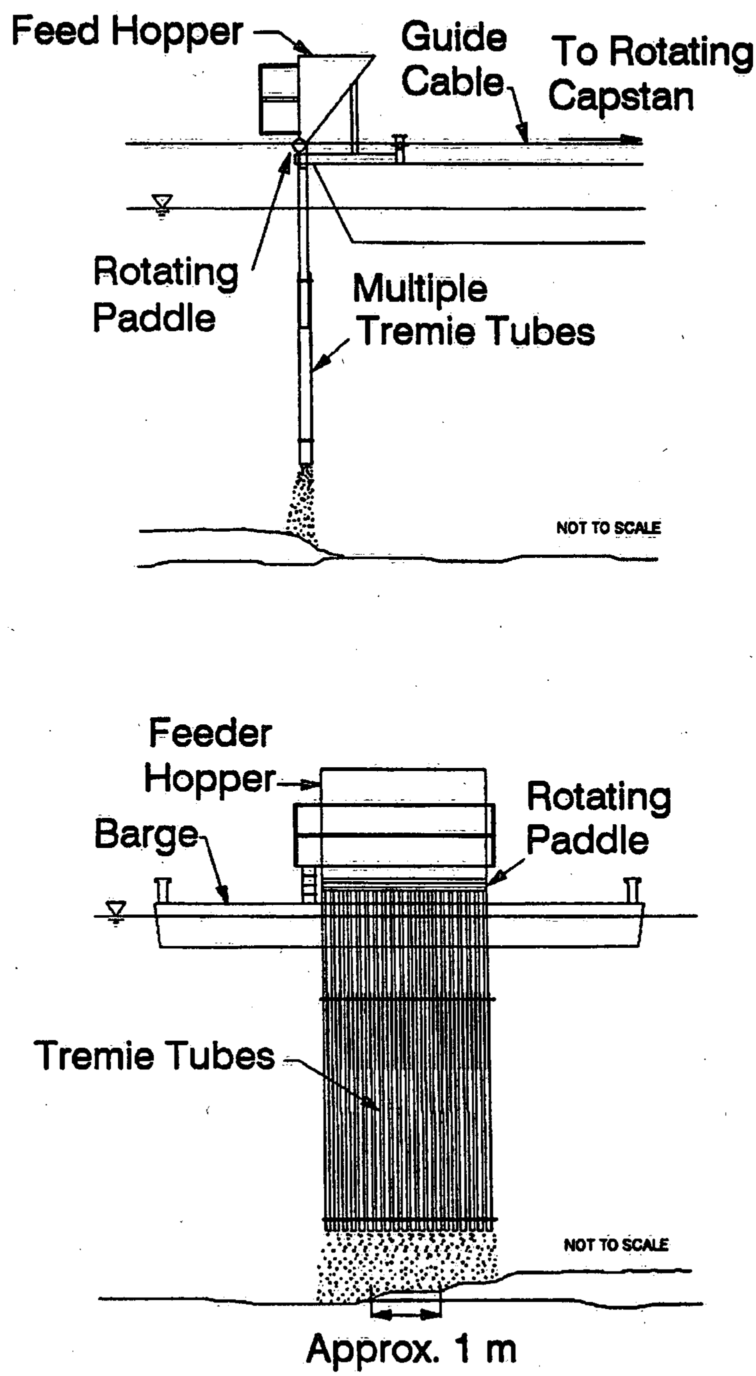

Fig. 5. Sand cap placement equipment.

estimated volume of 0.52 m^3 per minute. The assumed unit weight value of 14.5 kNm^{-3} was used for the mass-to-volume conversion (Kezdi 1974).

Sand was applied along 101 lines that were approximately 100 m long each, with east-west orientation. The route the barge took was either eastbound or westbound for any given line. These lines were spaced one metre apart. The total width of the 20 tremie tubes was the same as that of the hopper, i.e., 3 m. Each line in theory thus received three layers of sand (Fig. 5). The combined three layers of applied sand for each line were designed to produce a total cap thickness of 50 cm. Horizontal spreading of the sand was observed and documented by divers' observations, coring around the perimeter of the site, and a ROXANN survey described below in this paper.

Limitations

Throughout the project, down times occurred due to equipment malfunctioning, winds of over 30 km/h, and other problems such as large cobbles in the sand. Under optimum conditions, five lines per day were properly laid using about 400 tonnes of sand, in the time frame of about 10 hours.

Positioning

Horizontal and vertical positioning of the barge was controlled using a differential global positioning system (DGPS). A Trimble real-time-kinematic DGPS system was used with a locally placed transmitting antenna of known co-ordinates serving as a reference, in conjunction with direct measurements from satellites (total station). This provided a much higher accuracy than a conventional GPS, which relies solely on direct satellite transmissions. The accuracy of a conventional GPS is approximately ±100 m, whereas the total station DGPS used had an accuracy of ±0.1 m.

A satellite antenna was installed on the northwest corner of the hopper (the barge and hopper were of consistent orientation for the full duration of sand placement). A satellite receiver, radio transceiver and navigation computer were set up in the main tugboat. The computer display showed the exact horizontal and vertical location of the antenna, which was updated every second and recorded to an electronic file. These files were made into plots showing the exact route taken by the barge for each line (Fig. 6).

Monitoring

Monitoring took place during and after project operations, and still continues. Water depths before and after capping, suspended sediments in the water column, and weather data were all recorded.

Acoustic monitoring

Mounted to the tremie tubes were two upward and two downward facing transducers connected to several Lowrance X-16 echo sounders.

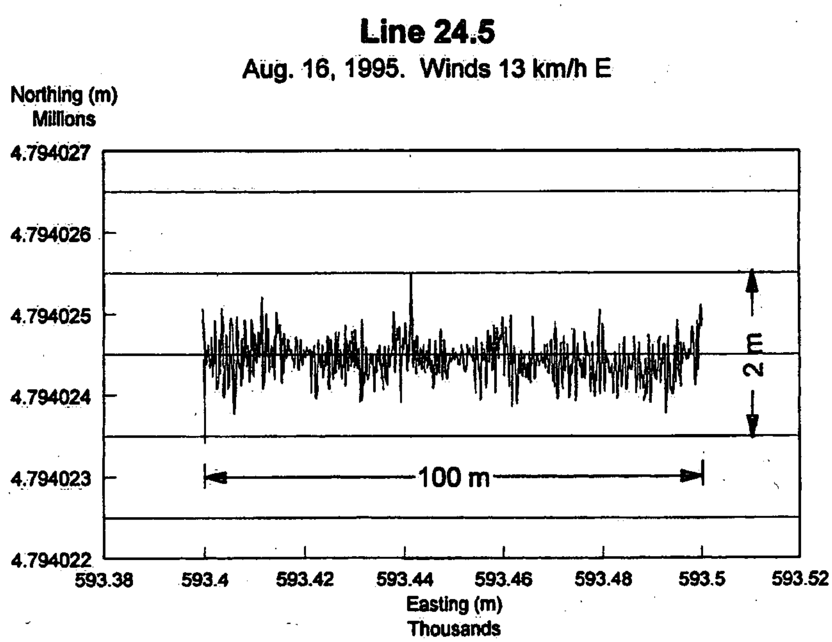

Fig. 6. Route of barge as measured by DGPS.

Two transducers were located on either side of the tremie tubes with one facing up and one facing down for each side. The transducer setup was designed to show the depth before and immediately after a layer of sand was deposited on any given spot. In addition, the upward-facing transducers allowed measurement of any possible tilt of the tremie tubes, shown by the difference in readings between the two transducers. Hard copy displays of the soundings were recorded by the sounders.

Multibeam echo soundings

On three separate occasions, multibeam echo soundings of the capping site were conducted by Public Works and Government Services Canada (PWGSC) using the boat *Ontario Surveyor*. These boat surveys were conducted before, during and after capping operations in October 1994, August 1995 and October 1995 respectively. The bathymetric charts resulting from the three surveys (electronic files and hard copies) were obtained courtesy of PWGSC.

ROXANN survey

Before and after capping operations, surveys of the cap site for sediment texture were undertaken. This involved using a commercially available acoustic bottom classification system (ROXANN), connected to an echo sounder and mounted on a steel work boat (N. Rukavina, NWRI, personal communication). The site was scanned in closely paced swaths in east-west and north-south directions, using the DGPS for accurate boat positioning. The signals received by ROXANN were automatically and continuously converted in real time to sediment types using the information on hardness and roughness of the sediment surfaces. In this manner, electronic colour sediment maps at a preselected scale were obtained. The ROXANN mapping proved to be highly consistent and it therefore appears ideally suited for monitoring of sand caps placed over fine-grained sediments. Presently, no information on cap thickness is obtained using this innovative technique, but attempts will be made to obtain sub-surface information using two different frequencies (N. Rukavina, NWRI, personal communication).

Turbidity

Monitoring of fines in the water column during cap placement was conducted using the acoustic Doppler current profiler (ADCP). The profiler was lowered by cable from a small boat that trolled around the cap site area during capping operations. The ADCP measured the density of sediment plumes (turbidity) and currents. Water samples were also taken during placement of the cap and analysed for total suspended solids (TSS).

Diving transects and observations

Before cap placement, divers installed two cables on the harbour bottom inside the cap site to use as diver guide lines. The cables were made of 5-mm (3/16 in.) polypropylene line and positioned about 1.5 m above the cap. These lines crossed near the centre of the site, ending outside of the site's four corners, in an "X" pattern, and facilitated the installations of settlement gauges and dialysis chambers (peepers) (Fig. 7).

Divers made underwater observations of the site following completion of the cap, noting cap coverage and status of settlement gauges, described below. On one occasion, the divers also measured sand thickness using a stainless steel 1-m long measuring rod. A pointed cone on the end of the rod flared out to a flat surface encircling the rod. The sand cap was punctured with the rod, and the rod slowly pulled back up until resistance from the sand against the flat base of the cone was encountered. Thickness of the sand cap could then be measured by aligning the cap surface with the rod at the point of resistance. This noted spot on the rod was then measured from the flat base of the cone. Eight measurements were collected at 5-m intervals within the capped area.

Vibracores

In addition to gravity cores taken before cap placement, vibracores, which penetrated the sand cap, were also collected at predetermined locations. Seven vibracores were taken at the cap site on August 26, 1995, and ten were taken on September 26, 1995. Following their arrival in the laboratory, all cores were X-rayed for sediment structure and density.

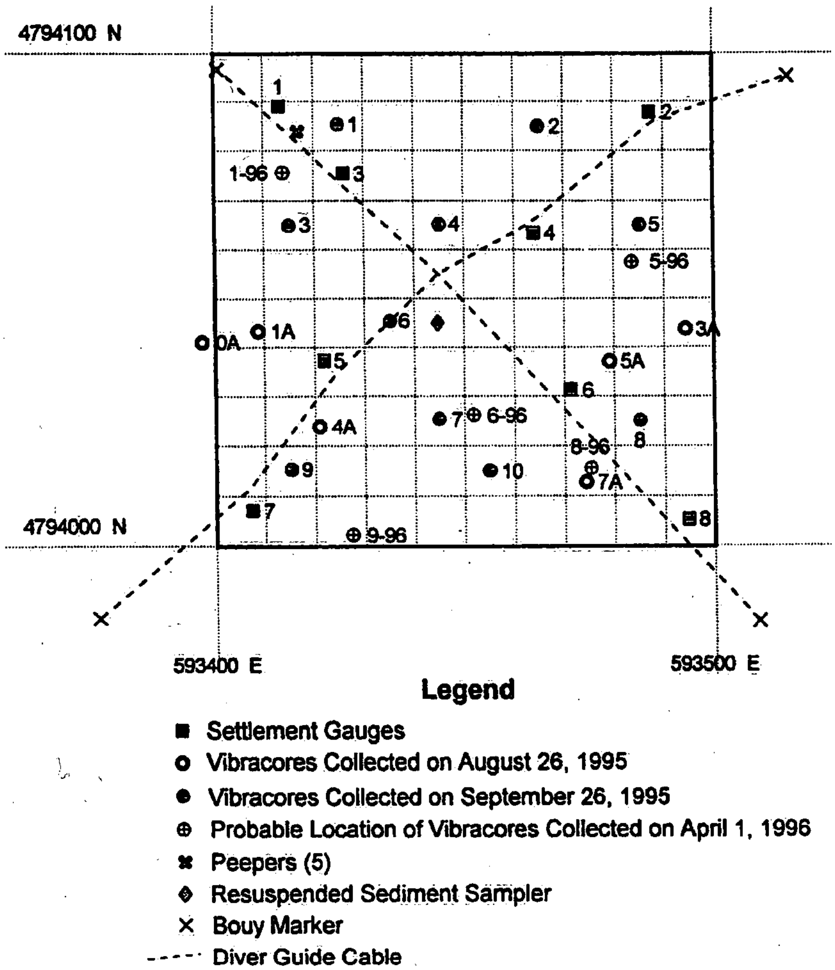

Fig. 7. Monitoring equipment and core locations at cap site.

Pore water monitoring

Following cap placement, five dialysis chambers or peepers (Rosa and Azcue 1993) were installed together at the north-west corner of the cap site (Fig. 7). The peepers consist of a porous membrane that covers a chamber filled with distilled water. The distilled water in the peepers is expected to be eventually replaced with surrounding pore water which can later be analyzed for chemical content. Two peepers were removed in 1995; the remaining ones were removed in subsequent intervals during 1996. The last peeper was removed on October 1, 1996 (F. Rosa, NWRI, personal communication). Results of pore water data will be compiled at a later date.

Consolidation

Eight settlement gauges were installed at the cap site prior to capping (Fig. 8). These were installed to measure both primary and secondary consolidation (Zeman and Patterson 1995), since the submerged weight of the sand cap was expected to significantly compress the underlying sediment. The gauges consisted of a vertical metal reference rod driven into the sediment, which passed through an aluminum tube attached to the centre of a square (1.2 m x 1.2. m) horizontal platform. A collar was attached to the vertical rod, and aligned with the top end of the aluminum tube. Measurements of consolidation could be taken by divers as the platform moved downward under the weight of the sand, leaving a gap between the aluminum tube and the collar. Settlement of the cap will continue to be monitored.

Compilation of positioning data

The positioning data collected by the DGPS unit were imported into a spreadsheet format, and a chart was created showing the precise route the barge took across each line (Fig. 6). From this information, any sway of the barge became very apparent, and the standard deviation for line accuracy was calculated. Fluctuations in sand cap thickness could be better explained with this data. Graphs were then created comparing the standard deviation of each line with the average wind speed occurring during sand placement on that line.

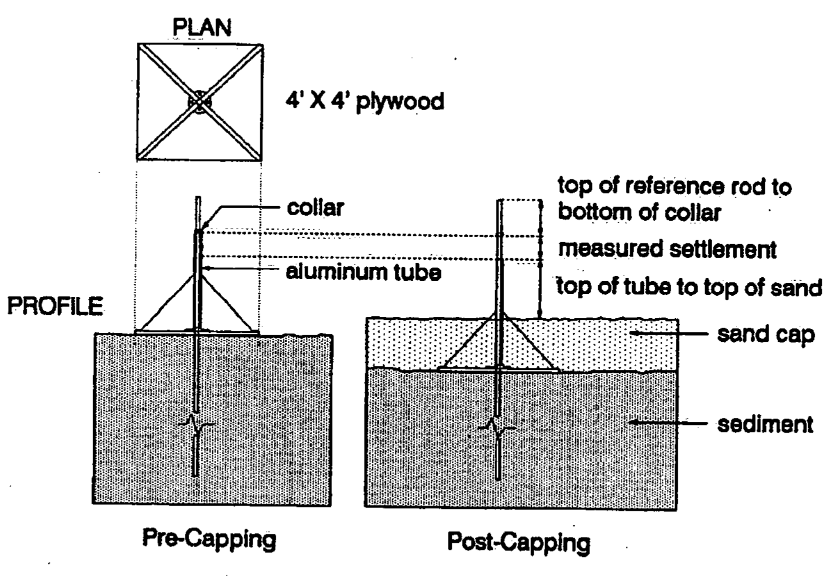

Fig. 8. Settlement thickness gauge.

Results

Subaqueous capping is a long-term solution, therefore overall assessment concerning the effectiveness of the cap takes years to determine. Potentially adverse effects to the cap, however, can be minimized with careful site selection (Zeman et al. 1992).

Water quality monitoring carried out during cap placement showed turbidity plumes around the area of sand placement. The preliminary results indicate that the suspended material appears to have been almost entirely composed of fines associated with the cap sand.

Two settlement gauges were damaged due to capping operations, and others were hard for the divers to find due to poor visibility. Initial readings taken in September 1995 of the remaining settlement gauges show consolidation to range between 6 and 8 cm. Monitoring of the gauges will continue in 1997. Consolidation data are required for estimates of pore water released from the sediment into the cap, and for the

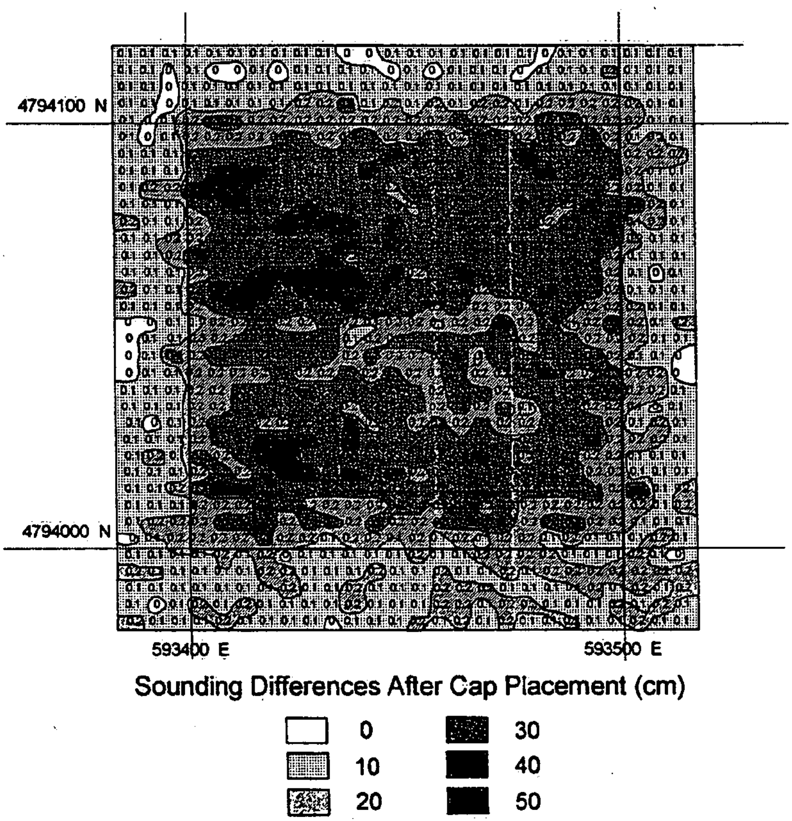

Fig. 9. Contour map obtained from comparison of two PWGSC echo soundings (October 1994 and October 1995).

interpretation of elevation changes of the cap surface (Zeman and Patterson 1995).

Depths taken from the October 1994 and October 1995 soundings were converted to spreadsheet format and compared. A contour map (Fig. 9) showing differences of depths between the two sets of soundings was created and compared to the vibracores. It should be noted that the actual thickness of the cap is greater because of consolidation of the underlying very soft sediments during placement. A map created using ROXANN data had similar patterns to the contour map.

Although the cap design thickness was 50 cm, the actual average cap thickness (post-construction) was 34 cm due to horizontal spreading of sand, possibly combined with a lower than required sand application rate. The average thickness (out of eight measurements collected at 5-m intervals) measured at the diving transect was 34 cm. The lower than expected thickness is still expected to be effective since a 50-cm cap is considered to be conservative. The design thickness of 50 cm is based on laboratory tests using highly mobile and non-adsorbing chemicals (Brannon et al. 1985). The vibracores also showed a sharp interface between the sand cap and sediments, which confirmed previous laboratory experiments carried out in a NWRI 3.6-m x 3.6-m x 3.7-m observation tank (Zeman 1994).

Based on data collected from the above, it was confirmed that the sand cap was successfully placed in the designated area with a minimum of sediment disturbance, and is expected to maintain its effectiveness.

Acknowledgments

The pilot project has been sponsored from its very beginning by the Great Lakes Cleanup Fund 2000 and NWRI. Thanks are extended to Ian Orchard, Carol Ancheta and Roger Santiago of Environment Canada (Ontario Region) for their considerable assistance with the preparation and supervision of the project. Project operations were conducted by Greenwood Environmental Inc. of Niagara Falls, Ontario. Additional technical support in sampling and monitoring was provided by NWRI staff in Technical Operations Section of Research Support Branch, Aquatic Ecosystems Restoration Branch, (Lake Remediation Project under Murray Charlton, and Sediment Remediation Project under Alena Mudroch). Norm Rukavina of New Technologies Research Branch supervised the ROXANN surveys and designed the acoustic monitoring system. Cam Halliday and Brian Carrigan of Public Works and Government Services Canada provided complete soundings before, during and after cap placement.

References

Brannon, J., R. Hoeppel, T. Sturgis, I. Smith and D. Gunnison. 1985. Effectiveness of capping in isolating contaminated dredged material from biota and the overlying water. United States Waterways Experiment Station, Vicksburg, Miss., Technical Report D-85-10.

Kezdi, A. 1974. Handbook of Soil Mechanics, vol. 1. Elsevier Scientific Publishing Company, New York.

Ministry of Environment and Energy for Ontario. 1994. Guidelines for the protection and management of aquatic sediment quality in Ontario. Queen's Printer for Ontario.

Rosa, F. and J.M. Azcue. 1993. "Peeper methodology" — a detailed procedure from field experience. NWRI Contribution No. 93-33.

Sumeri, A., T.J. Fredette, P.G. Kullberg, J.D. Germano, D.A. Carey and P. Petchko. 1991. Sediment chemistry profiles of capped in-situ and dredged sediment deposits: results from three US Army Corps of Engineers Offices. Reprint, Western Dredging Association Conference, 14-15 May 1991, Las Vegas, Nev.

Zeman, A.J. 1994. Subaqueous capping of very soft contaminated sediments. Can. Geotech. J. **31**(4):570-577.

Zeman, A.J. and T.S. Patterson. 1995. Evaluation of primary and secondary consolidation of Hamilton Harbour and Lake Ontario sediments due to in-situ capping. NWRI Contribution No. 95-02.

Zeman, A.J., T.S. Patterson, A. Mudroch, F. Rosa, T.B. Reynoldson and K.E. Day. 1995. Results of baseline geotechnical, chemical and biological tests for a proposed in-situ sediment capping site in Hamilton Harbour. NWRI Contribution No. 95-03.

Zeman, A.J., S. Sills, J.E. Graham and K.A. Klein. 1992. Subaqueous capping of contaminated sediments: annotated bibliography. NWRI Contribution No. 92-65.

Environment Canada Environnement Canada

Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

St. Lawrence Centre
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

Place Vincent Massey
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

Centre Saint-Laurent
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

Place Vincent-Massey
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada