PHYSICAL BARRIER TO REDUCE WP MORTALITIES OF FORAGING WATERFOWL

By Patricia A. Pochop,[1] John L. Cummings,[2] Christi A. Yoder,[3] and William A. Gossweiler[4]

ABSTRACT: White phosphorus (WP) has been identified as the cause of mortality to certain species of waterfowl at Eagle River Flats, a tidal marsh in Alaska, used as an ordnance impact area by the U.S. Army. A blend of calcium bentonite/organo clays, gravel, and binding polymers was tested for effectiveness as a barrier to reduce duck foraging and mortality. Following the application of the barrier to one of two contaminated ponds, we observed greater duck foraging and higher mortality in the untreated pond and no mortality in the treated pond after a year of tidal inundations and ice effects. Emergent vegetation recovered within a year of treatment. WP levels in the barrier were less than the method limit of detection, indicating no migration of WP into the material. Barrier thickness remained relatively stable over a period of 4 years, and vegetation was found to be important in stabilizing the barrier material.

INTRODUCTION

Since 1949, the U.S. Army has used the Eagle River Flats (ERF) of Fort Richardson, Ala., as an impact area for explosive ordnance. In 1980, hunters discovered an estimated 1,000–2,000 duck carcasses at ERF (Racine et al. 1992a). On February 8, 1990, the Army temporarily suspended firing into ERF because of a correlation between waterfowl mortalities and contamination of the flats by chemical debris from ordnance [i.e., white phosphorus (WP) (Racine et al. 1992b)]. In February 1991, WP ingestion was causally linked to waterfowl deaths (Racine et al. 1992a,b), and efforts to reduce hazards began.

ERF is an important staging area for waterfowl during spring and fall migration (Racine et al. 1993). The waterfowl species most susceptible to WP poisoning on ERF include mallards (*Anas platyrhynchos*), green-winged teal (*A. crecca*), northern pintails (*A. acuta*), trumpeter swans (*Cygnus buccinator*), and tundra swans [*C. columbianus* (Racine et al. 1992a)]. These waterfowl may mistake the hard, waxy WP pellets in the sediment as food/grit or simply ingest them incidentally (Racine et al. 1992b). The lethal dose (LD50) for mallards is estimated to be 4 mg/kg (Roebuck et al. 1998). Bald eagles (*Haliaeetus leucocephalus*), ravens (*Corvus corax*), and herring gulls (*Larus argentatus*) feed on dead and dying waterfowl and may be exposed to WP indirectly (Roebuck et al. 1994).

The problem with remediating areas contaminated with WP is that WP is persistent in aquatic environments (it can remain inert indefinitely) and does not readily oxidize in the anaerobic conditions that exist at ERF (Racine et al. 1992a,b, 1993; Walsh et al. 1996). Walsh (1994) described in detail the chemical and physical properties of WP. Records on the amount of WP fired into ERF between 1949 and 1987 are unavailable, but between 1987 and 1990 over 900 kg of WP was fired into ERF (Racine et al. 1992b; Clark et al. 1998). By 1991, detonation of WP rounds into ERF was eliminated. Sediment samples testing positive for WP in ERF are highly variable in concentration both between and within samples from ponded areas; therefore, the concentration and mass values are considered less reliable than presence/absence data (Racine et al. 1993). Furthermore, it is not known how deep into the sediments WP exists (Racine et al. 1993). Limited WP sampling has been conducted to depths of 60 cm, and samples have tested positive to depths of 55 cm (CRREL 1994). Complications of sampling vertically exist due to the presence of unexploded ordnance.

Several methods were screened and excluded as remediation technologies on ERF. Among the methods that were excluded were dredging (not cost effective); geosynthetics and other capping methods (eliminated based on pilot studies); air sparging, chemical oxidation, explosive charges, and enhanced sublimation/oxidation (ineffective based on pilot studies); and hazing and chemical bead repellents [only considered as interim methods (CH2MHILL 1997)]. The U.S. Army continues to use ERF as a training area in the winter, when ice is frozen into the ground to a depth of 15 cm to reduce the chance of redistributing the WP. Therefore, methods that are still being tested and considered for use at ERF must be able to withstand this training and the environmental conditions that exist at ERF. These methods are containment (specifically the barrier/capping method described), monitoring (natural processes removing some WP from the system), and pond draining by both breaching and pumping (CH2MHILL 1997). Natural size reduction of WP is occurring on ERF (Walsh et al. 1996), but periodic flooding by tide action will prevent permanently ponded areas from allowing oxidation of WP without some type of remedial action (i.e., pond pumping or breaching) to accelerate the process. However, even pond pumping or breaching will have limited effectiveness because drying the sediments in some areas may not be cost effective as a result of a high water table, dense vegetation, etc. Drying the sediments adequately is the key to oxidation of WP on ERF (Walsh et al. 1996). A method that will allow an area to be mitigated by use of a barrier/capping material in conjunction with pond pumping, pond breaching, and monitoring is needed to offer a total repertoire of alternatives for remediating ERF.

WP has been found in at least 71 hazardous waste sites on the National Priorities List and as the U.S. EPA evaluates more sites, this number may increase (*Toxicological* 1994). In addition, sites with polychlorinated biphenyl contaminated sediments from industrial operations are being considered as candidates for capping/barrier technologies (Hull et al. 1998). Capping/barrier technologies are used for containment. When implemented properly, capping/barrier technologies do not al-

[1]Wildlife Biologist, U.S. Dept. of Agr., Animal and Plant Health Inspection Service, Wildlife Services, Nat. Wildlife Res. Ctr., 4101 LaPorte Ave., Fort Collins, CO 80521.

[2]Res. Wildlife Biologist, U.S. Dept. of Agr., Animal and Plant Health Inspection Service, Wildlife Services, Nat. Wildlife Res. Ctr., 4101 LaPorte Ave., Fort Collins, CO.

[3]Grad. Student, Dept. of Fisheries and Wildlife Biol., Colorado State Univ., Fort Collins, CO 80524.

[4]Eagle River Flats Proj. Mgr., U.S. Army 6th Infantry Div. (Light), Envir. Ctr., Fort Richardson, AK 99505.

Note. Associate Editor: Wu-Seng Lung. Discussion open until July 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 15, 1998. This paper is part of the ***Journal of Environmental Engineering***, Vol. 126, No. 2, February, 2000. ©ASCE, ISSN 0733-9372/00/0002-0182–0187/$8.00 + $.50 per page. Paper No. 18113.

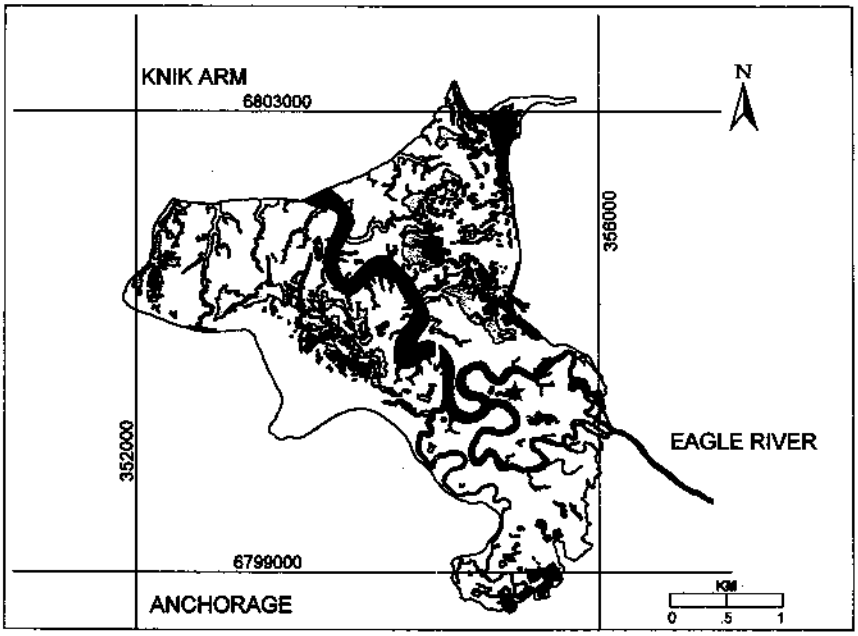

FIG. 1. Eagle River Flats, Fort Richardson, Ala., Showing Relative Locations of Control Enclosure in Area C (☆) and Treated Enclosure on Racine Island (*)

low degradation of contaminants or allow contaminants to reenter the exposure pathway. In 1993, Fort Richardson was proposed for inclusion on the National Priorities List. Therefore, ERF falls under the Comprehensive Environmental Response, Compensation, and Liability Act process. Potential remediation actions that are practical, effective, and capable of being readily implemented need to be developed for ERF (CH2MHILL 1994a) and other hazardous waste sites. On ERF, the safety of personnel implementing the remediation technology is a high priority because of the presence of unexploded ordnance. One strategy that could reduce the presence of personnel needed to implement the technology and that might prevent ingestion of WP by waterfowl is the use of aerially applied physical barriers upon the substrate.

STUDY SITE

ERF is a 1,000-ha tidal marsh located north of Anchorage on the Fort Richardson Military Reservation (61°17.7′ N, 149°39.7′ W). For this study, we used Area C and Racine Island (Fig. 1). Sampling at both sites confirmed high contamination with WP.

Area C includes a single large pond (~10 ha) with a cratered bottom (Walsh et al. 1996). Within the pond, in 1994, we built a 40 × 80 m (3,200 m^2) control enclosure. In 1995, we installed three pairs of tide plots to the northwest of the control enclosure. One of each of the three pairs of plots was installed with a form to measure vertical movement of the physical barrier, and one was installed without a form to measure horizontal flow of the barrier.

Racine Island includes a small pond with a large number of water-filled ordnance impact craters (Fig. 2). In 1994, this approximately 25 × 160 m (4,000 m^2) area was fenced to serve as the treated area. In 1995, three pairs of tide plots were installed in the northwest corner of the site as described for Area C.

Enclosures were fenced with polypropylene netting (2-cm mesh) to a height of 2 m above the sediment. The netting was staked to the ground using landscaping pins (30 cm in length) at approximately 60-cm intervals. Ducks were wing-clipped before placing them into enclosures.

FIG. 2. Treated Enclosure on Racine Island. White Line Delineates Perimeter of Enclosure

METHODS

Application

The experimental product (AquaBlok) is manufactured by NewWaste Concepts, Inc. (Erie, Mich.) and consists of a blend of calcium bentonite/organo clays, gravel, and polymers, which bind together to form a sealant/physical barrier. These bentonite/organo clays had total and extractable Se concentrations consistently below analytical detection limits (total Se <0.05 ppm, extractable Se <0.071 mg/L). After manufacturing, the experimental product looks similar to gravel except it is covered with a clay/polymer coating. When this barrier material comes into contact with water, it swells up to 3 times its size and takes on the appearance of a clay/gravel mat.

In 1994, we prepared 148,300 kg of the barrier material on site in an 8-m^3 cement mixer. PVC bulk drop bags (model HD 32-36, Springfield Special Products, Springfield, Mo.) were used to apply the barrier material. Bags were loaded with up to 2,500 kg of the barrier material and then rigged to a Blackhawk helicopter for application. The barrier material was applied in 1.8-m swaths from a height of about 27 m at an airspeed of approximately 8 km/h. Fifty-seven loads were applied during 9 h over 2.5 days. To ensure adequate coverage of the treated area, about 7,100 kg of prepared barrier material was applied outside of the fenced area of the treated pen. In 1995, two craters believed to have been inadequately covered were retreated with barrier material (300 kg).

WP Sampling

In 1994, before the barrier application, we collected 30 sediment samples from the control enclosure and 29 from the treated enclosure for WP analysis; samples were collected at 10-m intervals on a marked grid. In 1995, we collected 15 samples of the barrier material from immediately outside or inside the treated pen for WP analysis; samples were collected near 1994 sample locations. Any samples taken from inside the pen were replaced with new barrier material to reduce any holes that would affect the integrity of the barrier.

Because of the presence of unexploded ordnance, intrusive soil sampling is not allowed on ERF; therefore, only surface samples were collected (CH2MHILL 1994b). Each sample was collected to an approximate depth of 3–5 cm from a 30-cm^2 area, placed in an acid-washed 500-ml sample jar, and sent to a contract laboratory (Waterways Experiment Station, Vicksburg, Miss., in 1994; ChemTrack, Anchorage, Ala., in 1995) for gas chromatographic analysis. The contract laboratories followed the analytical method developed by Walsh and Taylor (1993). The method limit of detection (MLOD) was 0.001 μg WP/g sediment.

Barrier Thickness

In 1994, at 24-h posttreatment, 10 core samples were collected using an 8-cm-diameter plastic tube to determine the thickness of the physical barrier. The tube was inserted by hand vertically through the barrier to a depth of approximately 30 cm. Insertion by hand of a plastic sampling device was not considered an intrusive sampling method. A caliper was used to measure the thickness in four locations equidistant around the core and an average was calculated. In 1995, 1996, and 1997, core samples were again collected by the same method to determine the thickness of the physical barrier and sedimentation.

Waterfowl Behavior

During 1994, to establish baseline mortality data prior to treatment, 24 captive-reared wing-clipped mallards from sex-by-size classes were randomly assigned to each of the two test enclosures for 10 days. Surviving mallards were removed before treatment. After the physical barrier was applied and allowed to settle for about 45 h, two new groups of 24 wing-clipped mallards were placed into each test enclosure. These ducks remained in the enclosures 20-days posttreatment.

We observed mallards from a tower near each enclosure to quantify foraging activity. Observations in both enclosures occurred daily between 0700–1100 and 1600–2000 h (60 min/period). At 1-min intervals, an observer recorded the number of mallards feeding or loafing in each pen. Feeding was defined as ducks dipping beneath the water, and loafing was defined as all activity other than feeding. On a daily basis, we alternated the order in which pens were observed during the morning and afternoon. Percent feeding activity was based on the number of feeding bouts recorded (morning plus evening observations) divided by the total number of feeding bouts possible if all ducks present fed for the entire period.

In 1995, 24 wild-caught wing-clipped mallards were placed into the treated pen for 46 days to quantify waterfowl mortality. Observations of foraging activity were prevented by the height of the vegetation. However, duck foraging behavior was observed to occur during visits to the site. We conducted surveys via helicopter or foot (around the perimeter of the pen) to determine the number of live or dead mallards in the pen each day.

In 1994, we were able to conduct carcass searches on foot outside the test enclosure because vegetation height did not interfere with observations of carcasses. However, in 1995, vegetation height may have interfered with the observers ability to locate carcasses. Therefore, an individual on a small rubber raft was maneuvered throughout the pen by individuals outside of the test enclosure to determine whether any carcasses were present that could not be detected using other methods (i.e., helicopter or foot patrol outside the enclosure). Throughout testing, supplemental food was available ad libitum on two floating platforms in each pen. At the end of each observation period, all dead birds were collected, and a subsample was selected for WP analysis as described by Roebuck et al. (1998). The MLOD was 0.01 μg WP/g tissue.

Vegetative Recovery

Photographs of the treated pen were taken from a height of approximately 240 m during July 21, 1991, August 30, 1994, August 16, 1995, and June 11, 1997, to determine vegetative recovery. A grid (1 × 1 cm) was overlaid on each photograph, and the percent vegetative coverage was estimated. Values of all cells covering the grids were summed and divided by the total number of cells to determine the enclosure coverage.

Tidal Impacts

On May 10, 1995, three paired plots were established on Racine Island and in Area C (six plots per site) to measure vertical displacement and horizontal movement of the physical barrier relative to tide action. In one plot, a 1 × 1 m square metal form (8 cm in height) was pushed into the sediment so that the top of the form was even with the substrate surface. The sediment inside each of these forms was removed to a depth of 8 cm, and the barrier material (50 kg/plot) was poured into the form and spread evenly. In these plots, the purpose was to measure vertical displacement of the barrier material (i.e., how much the barrier erodes). In the remaining plot, a square metal form (1 × 1 × 0.08 m) was placed on top of the sediment, the barrier material was applied into the form, spread evenly, and then the form was removed. Metal stakes (0.8-cm diameter × 90 cm length) were placed in the corners of the plot with the form removed to mark the corners of the original barrier application. From each corner of each plot with the form removed, stakes were placed extending out of the plot along the length of each axis at 30 and 60 cm. In these plots the purpose was to measure horizontal movement of the barrier material (i.e., how much the barrier flowed). Pairs of plots (i.e., a plot with a form and a plot without a form) within each area were established at water level and at 30 and 60 cm below water level, depending upon the pond bottom (i.e., the two deeper pairs of plots on Racine Island were placed in craters).

RESULTS

WP Sampling

During 1994, prior to application of the barrier, WP concentrations from sediment samples in the control pen ranged from less than the MLOD = 0.01 μg WP/g sediment to 3.4 μg/g ($\bar{X}$ = 0.16 ± 0.13 SE). Samples in the treated pen ranged from less than the MLOD to 19.0 μg/g ($\bar{X}$ = 1.59 ± 1.06 SE).

During 1995, WP concentrations from barrier samples in the treated pen ranged from less than the MLOD to 0.02 μg/g ($\bar{X}$ = 0.01 ± 0.01 SE).

The level of concern for WP is that it is present in amounts that are killing waterfowl. Cleanup of ERF will not be considered effective until mortality levels reach the same levels as in nearby marshes.

Barrier Thickness

Over level ground (including the pool) the mean thickness of the barrier ranged from 5.2 to 9.8 cm from 1994 through 1998 (Table 1). Craters were more unevenly covered with the thickness ranging from 7.4 to 16.1 cm. Sedimentation on top of the barrier ranged from 0.5 to 0.7 cm.

TABLE 1. Barrier Thickness (cm) and Sedimentation from 1994 through 1997, at ERF

Year (1)	Thickness ($\bar{X}$ ± SE) 1994 (2)	1995 (3)	1996 (4)	1997 (5)
Level ground	6.2 ± 1.3	5.2 ± 0.5	9.8 ± 0.9	7.5 ± 1.0
Craters	16.1 ± 4.4	14.5 ± 4.6	7.4 ± 0.1	8.9 ± 0.9
Sedimentation	—	0.7 ± 0.1	0.6 ± 0.2	0.5 ± 0.2

Waterfowl Behavior

Prior to the application of the physical barrier in 1994, 1 of 24 mallards in the control enclosure and 9 of 24 mallards in the treated enclosure survived [Fig. 3(a)]. Following the barrier application, 0 of 24 mallards in the control enclosure and 21 of 24 mallards in the treated enclosure survived [Fig. 3(b)]. All three birds in the treated enclosure succumbed late in the posttreatment period (days 14, 15, and 16), probably caused by inadequate barrier coverage over two craters (all three ducks within the same 2-m^2 area). Prior to the barrier application, there was greater foraging activity in the enclosure slated for the treatment than in the control enclosure ($\bar{X}$ = 34% versus 15%, respectively; Fig. 4). Foraging activity following the barrier application was greater in the control enclosure ($\bar{X}$ = 41% versus 8% treated). Also, mallards in the treated enclosure consumed more supplemental feed.

Following the test period, a total of seven mallards, one from control and two from treated enclosures during the pretreatment period and two from control and two from treated enclosures during the posttreatment period, were analyzed for WP residues. Six of the seven mallards analyzed for WP concentrations had detectable amounts in the digestive tract and/or fat. The duck that had no detectable amounts of WP was sampled only from the gizzard and fat (instead of the entire digestive tract) but showed signs of WP intoxication before death (lethargic, difficulty breathing, and convulsions).

In 1995, all mallards were observed to survive; no carcasses

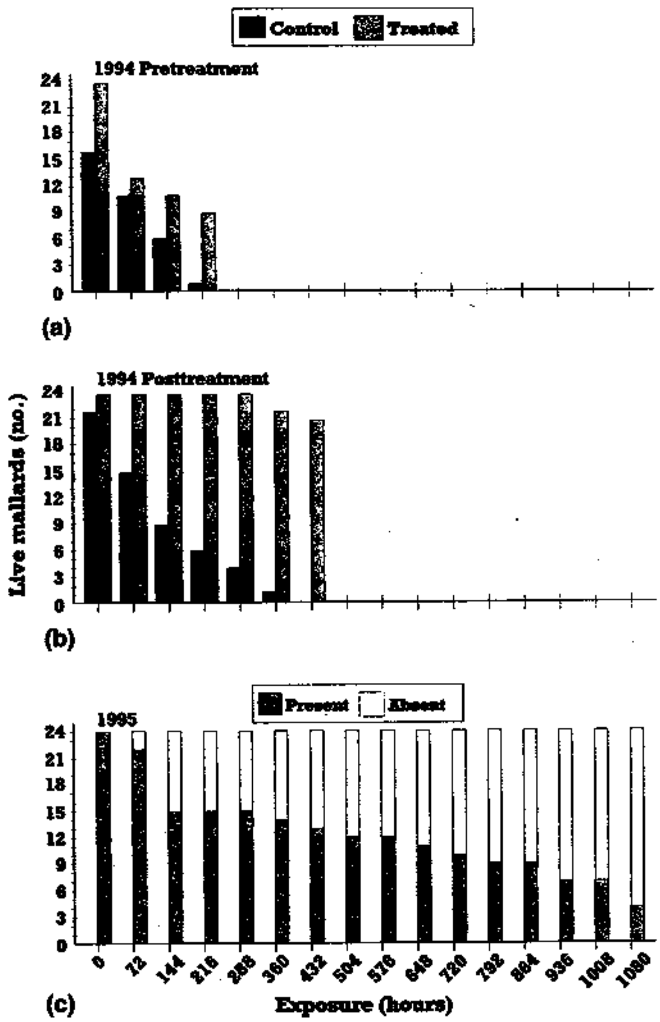

FIG. 3. Counts of Penned Live Mallards (n = 24) at ERF in: (a) Control and Treated Pools during Pretreatment (July 1–10, 1994); (b) Control and Treated Pools during Posttreatment (July 15–August 4, 1994); (c) Treated Pool (July 25–September 9, 1995). In 1994, Absence of Live Mallards Was Confirmed by Observations of WP-Affected Mallards and Collection of Carcasses. In 1995, Counts Were Adjusted for Observer Error; Reduced Number of Mallards in Pen Was Attributed to Ducks Flying over Perimeter Fence (i.e., No Affected Mallards or Carcasses Were Observed). In All Graphs, Exposure Is Time That Mallards Spent in Pens Either Prior to Death or Prior to Release

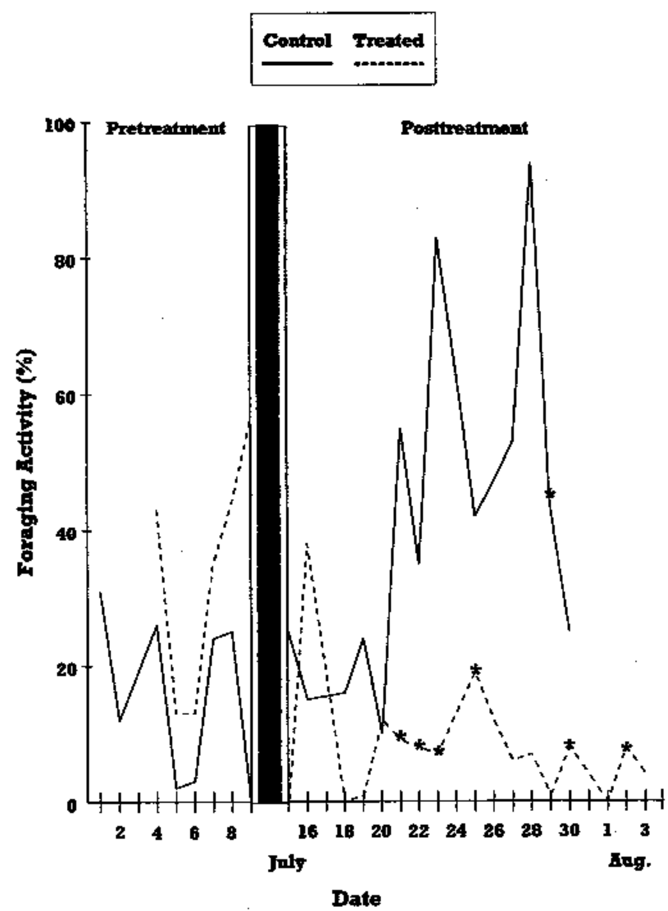

FIG. 4. Mallard Foraging Activity in Control and Treated Pools, July 1–August 4, 1994, at ERF. *Mallards Were Observed Consuming Supplemental Feed

ological forces should last indefinitely with regular maintenance. However, catastrophic events could impact the life of a capping/barrier material. Events such as 100-year storms and earthquakes could cause failure of any system that contains contaminants. Removing contaminants is the only way to safeguard an area from recontamination in the event of catastrophes. However, there are instances at specific sites where the contaminant cannot be either safely or economically removed without causing more severe impacts on the environment (Hull et al. 1998). On ERF, contaminants are being removed in areas where this is a cost-effective alternative. However, there are areas where this is not possible. Therefore, the investigation of this barrier/capping material is ongoing. Earthquakes are a common occurrence in Alaska. Because of the plastic nature of this barrier/capping material, if the ground should shift to the point where the contaminants in the treated area are exposed, the material should eventually fill this newly created void. For example, observations of the barrier being stepped on by researchers showed that upon reinundation of the area by water, the barrier would re-cover the impacted area within 24 h. However, if the area were to be heavily impacted by a catastrophic event, a new application of the barrier material over the exposed area could be necessary.

The cost of the initial application of the barrier to the 0.5 ha used in the 1994 study was about $26,000 ($0.15/kg materials and $0.02/kg manufacturing). This cost did not include the gravel (supplied by the U.S. Army), labor (2 U.S. Army personnel to operate heavy equipment), or application (9 h of Blackhawk helicopter application time and 1.5 h of UH1 helicopter support time, supplied by the U.S. Army). It cost an additional $1,350 ($4.50/kg materials, manufacturing, and labor) not including application (0.5 h of UH1 helicopter time supplied by the U.S. Army) to treat the two craters in 1995 that were unevenly covered from the previous year's application. The cost to apply this physical barrier on an operational level was estimated at $80,000/ha by the manufacturer (excluding application). Large areas (>10 ha) would cost less on a per hectare basis because the costs of mass producing the material will decrease with greater quantities.

CONCLUSIONS

This physical barrier is less expensive than other methods of cover (i.e., plastic membrane barrier system). In addition, Hull et al. (1998) discussed the advantages of this barrier material over sand as a capping/barrier technique. It is possible to manufacture the product on-site, thereby reducing costs. This physical barrier is easy to apply, with several application methods, and there are specific reapplication methods that can be used (i.e., spot treating can be done using either hovercraft or helicopters). Bentonite slurries and mats are used extensively in landfill caps, pond liners, and in drilling. They are one part of a multilayer defense in the minimization of resuspension of contaminants.

Future investigations at ERF will investigate another method for applying the barrier material by using low ground-pressure vehicles over ice. In addition, the barrier material may be formulated with a topcoat to delay activation of bentonite until after the ice melts.

ACKNOWLEDGMENTS

The writers thank Steve Greiner [National Wildlife Research Center (NWRC), Fort Collins, Colo.] and Ken Gruver (NWRC) for quality assurance/quality control inspection; Tim Johnson and Tom Nachtman (New Waste Concepts, Inc., Erie, Mich.) for technical support; Corey Rossi [Wildlife Services (WS), Palmer, Ala.], Steve Runyon (WS), John Spiegle (WS), and Ken Tope (NWRC) for field assistance; Bill Roebuck (Dartmouth Medical School, Hanover, NH) for analyzing WP concentrations in mallards; the U.S. Army National Guard for air support, Fort Richardson, Ala.; the U.S. Army 176th Ordnance Detachment, Fort Richardson, Ala., for clearing paths of unexploded ordnance; the Public Works-Environmental staff of Fort Richardson, Ala., particularly Laurie Angell and Bill Smith, for logistical assistance; and the Cold Regions Research and Environmental Laboratory, Hanover, NH, for technical assistance. The writers gratefully acknowledge Don Elias (NWRC), Russ Mason (NWRC), and Mike Pipas (NWRC) for critical reviews of earlier manuscript drafts and the U.S. Army 6th Infantry Division (Light), Environmental Center, Fort Richardson, Ala., for project funding. Use of a company or trade name does not imply U.S. government endorsement of commercial products. Guidelines outlined by the Animal Welfare Act and the NWRC Animal Care and Use Committee were followed during this study.

APPENDIX. REFERENCES

CH2MHILL. (1994a). "Comprehensive evaluation report, Eagle River Flats, Fort Richardson, Alaska." *Rep. No. DACA85-92-D-0007 Prepared for Dept. of Public Works, U.S. Army Garrison, Anchorage, Alaska.*

CH2MHILL. (1994b). "Eagle River Flats, quality assurance program plan." *Rep. No. DACA85-92-D-0007 Prepared for Dept. of Public Works, U.S. Army Garrison, Anchorage, Alaska.*

CH2MHILL. (1997). "Operable Unit C: Final feasibility study report." *Rep. No. DACA85-95-D-0015 Prepared for Dept. of Public Works, U.S. Army Garrison, Anchorage, Alaska.*

Clark, L., Cummings, J. L., Davis, J. E., and Pochop, P. A. (1998). "Evaluation of a macro encapsulated repellent to reduce risk of white phosphorus ingestion by waterfowl foraging in a contaminated marsh." *Int. Biodeterioration and Biodegradation*, 42, 135–145.

CRREL. (1994). "Appendix B: Data for samples collected in areas A, B, C, C/D, D, the bread truck pond, Racine Island and the mudflats." *in* C. H. Racine and D. Cate, eds. *Interagency Expanded Site Investigation: Evaluation of White Phosphorus Contamination and Potential Treatability at Eagle River Flats, Alaska—FY93 Final Rep. Prepared for Directorate of Public Works, U.S. Army, Alaska,* C. H. Racine and D. Cate, eds., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 371–396.

Hull, J. H., Jersak, J. M., Pochop, P. A., and Cummings, J. L. (1998). "Evaluating a new in-situ capping technology for mitigating contaminated sediments." *Proc., Fifteenth World Dredging Congress*, Vol. 1. 555–576.

Lawson, D. E., Bigl, S. R., Hunter, L. E., Nadeau, B. M., Weyrick, P. B., and Bodette, J. H. (1995). "Physical system dynamics, white phosphorus fate and transport, remediation and restoration, Eagle River Flats, Fort Richardson, Alaska." *Interagency Expanded Site Investigation: Evaluation of White Phosphorus Contamination and Potential Treatability at Eagle River Flats, Alaska—FY94 Final Rep., 2 Vol. Prepared for Directorate of Public Works, U.S. Army, Alaska,* C. H. Racine and D. Cate, eds., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 53–186.

Racine, C. H., et al. (1992a). "White phosphorus poisoning of waterfowl in an Alaskan salt marsh." *J. Wildlife Diseases*, 28(4), 669–673.

Racine, C. H., et al. (1993). "White phosphorus contamination of salt marsh pond sediments at Eagle River Flats, Alaska." *CRREL Rep. 93-17.* U.S. Army Environmental Center, National Technical Information Service, Springfield, Va.

Racine, C. H., Walsh, M. E., Collins, C. M., Calkins, D. J., Roebuck, B. D., and Reitsma, L. (1992b). "Waterfowl mortality in Eagle River Flats, Alaska: The role of munition compounds." *CRREL Rep. 92-5, CETHA-IR-CR-91008,* U.S. Army Toxic and Hazardous Materials Agency, National Technical Information Service, Springfield, Va.

Roebuck, B. D., Nam, S., MacMillan, D. L., Baumgartner, K. J., and Walsh, M. E. (1998). "Toxicology of white phosphorus (P_4) to ducks and risk for their predators: Effects of particle size." *Envir. Toxicology and Chem.*, 17(3), 511–518.

Roebuck, B. D., Walsh, M. E., Racine, C. H., Reitsma, L., Steele, B., and Nam, S. (1994). "Predation of ducks poisoned by white phosphorus: Exposure and risk to predators." *Envir. Toxicology and Chem.*, 13(10), 1613–1618.

Toxicological profile for white phosphorus and white phosphorus smoke. (1994). Agency for Toxic Substances and Disease Registry, U.S. Department of Health and Human Services, Public Health Service, Atlanta.

Walsh, M. E. (1994). "White phosphorus evaluation and characterization: Review of chemical and physical properties of WP." *Interagency Expanded Site Investigation: Evaluation of White Phosphorus Contamination and Potential Treatability at Eagle River Flats, Alaska—FY93 Final Rep. Prepared for Directorate of Public Works, U.S. Army, Alaska,* C. H. Racine and D. Cate, eds., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, 111–131.

Walsh, M. E., Collins, C. M., and Racine, C. H. (1996). "Persistence of white phosphorus (P_4) particles in salt marsh sediments." *Envir. Toxicology and Chem.*, 15(6), 846–855.

Walsh, M. E., and Taylor, S. (1993). "Analytical method for white phosphorus residues in munitions-contaminated sediments." *Anal. Chim. Acta.*, 282, 55–61.