Estimated Particulate Emissions by Wind Erosion from the Indiana Harbor Confined Disposal Facility

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Abstract: A confined disposal facility (CDF) is being designed for 3.5 M m^3 of contaminated sediments dredged from the Indiana Harbor Canal at East Chicago, Ind. The sediment will be placed in two cells enclosed by earthern berms about 9 m tall and cover about 36 ha. The air registration for the facility poses limits on particulate emissions; however, very little is known of the potential for particulate emissions from hydraulically placed dredged material. Therefore, the purposes of this study were to (1) determine temporal wind erodibility of the sediments; (2) estimate potential particulate emissions from wind erosion during CDF operations; and (3) simulate emission control measures that allow the CDF to comply with allowable emissions. A composite sample of Indiana Harbor sediment was placed in outdoor sediment bins at Manhattan, Kan., and variations in sediment wind erodibility parameters were determined over a 22 month period. In general, sediment erodibility increased with freeze/thaw cycling, but decreased during the summer. Next, the Hydrologic Evaluation of Landfill Performance and the Primary Consolidation, Secondary Compression and Desiccation of Dredged Fill models were used to determine periods when the CDF cell surfaces would be saturated. Finally, the Wind Erosion Prediction System model was used to estimate potential suspended particulate emissions from the CDF during unsaturated periods. Hydraulic placement of the sediments in the cells will result in a sand bed at the north end of the cells that needs to be stabilized to prevent abrasion of the downwind area. Even with the sand bed stabilized, the simulation results showed that additional erosion control would likely be needed. Snow fences, short barriers, and stabilized strips were simulated as potential erosion controls. The results showed any of these could provide adequate reductions in emissions to meet the target emission levels.

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CE Database subject headings: Wind; Erosion; Sediment; Simulation models; Emissions; Harbors; Indiana.

Introduction

A confined disposal facility (CDF) located in East Chicago, Ind. is being designed by the U.S. Army Corps of Engineers (USACE) that includes two sediment cells that encompass about 36 ha. The selected site was an abandoned, highly contaminated, industrial area that required considerable remediation before beginning construction of the CDF impoundment. The CDF will contain 3.5 M m^3 of contaminated sediments dredged from Indiana Harbor and will be operated for three decades before it is closed and capped. The sediments are contaminated with PCBs, PAHs, and heavy metals and therefore the air registration for the facility has posed an annual limit on particulate and volatile emissions. The sediments will be hydraulically placed as slurry, so particulate emissions from the wet sediment will be negligible until the dredged material is dewatered.

During initial assessment, several sources of particulate emissions associated with various scenarios for operating the CDF were identified. When these were evaluated, all were estimated to be minor sources, except for potential particulate emissions by wind erosion from the sediment cells (Cieniawski 2000). Hence, as part of the design process, estimates of potential particulate emissions were deemed necessary to support required operational assessments for the CDF. However, little was known about the changes in wind erodibility of the dredged sediments as they dried.

Hence, the purposes of this study were to: (1) determine wind erodibility of the sediments as they dry and weather; (2) estimate potential particulate emissions from wind erosion during CDF operations; and (3) simulate a range of emission control measures that would allow the CDF to maintain particulate emissions below the limit set by the CDF air registration. The methodology for testing sediment wind erodibility and applications of the Wind Erosion Prediction System (WEPS) model illustrated in this study can likely be applied to other sites with exposed dry sediments including dredged sediments, tailings ponds, and dry lakebeds.

Materials and Methods

Sediment Bin Design and Treatment

To determine the temporal wind erodibility of the sediments, two outdoor sediment bins were constructed on a sod field at Manhattan, Kan. (Fig. 1). Wind barriers (1.2 m tall snow fences) were used to shelter the bins from erosive winds and to exclude ani-

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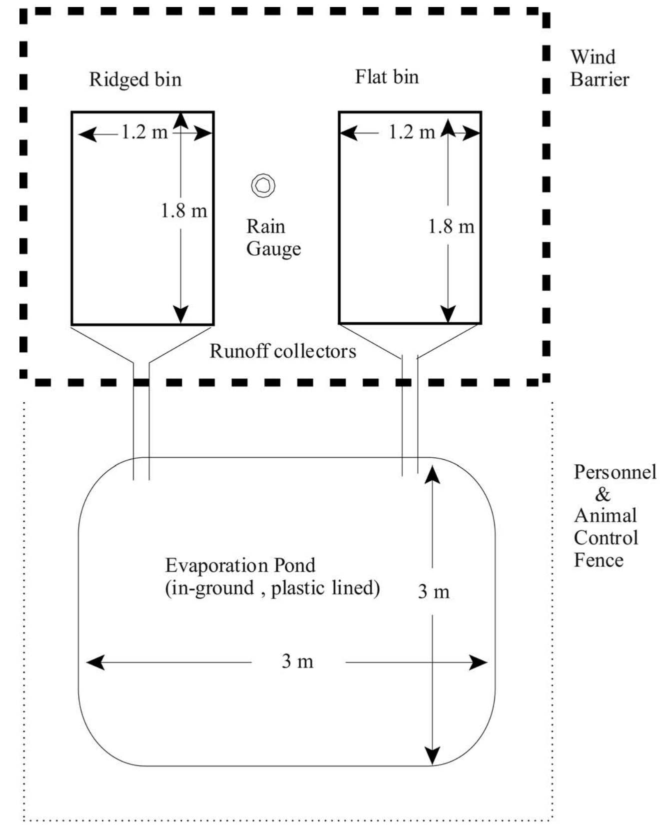


Top View

Fig. 1. Sediment bins and evaporation pond at Manhattan, Kan. field site

mals from the evaporation ponds. About 2.6 m^3 of sediments dredged from Indiana Harbor were placed in the bins in August 2003. All drainage and runoff from the bins were collected by galvanized sheet metal collectors connected to plastic pipes that conveyed the runoff to an impermeable pond lined with two layers of plastic sheeting. One sediment bin was "tilled" to create two, 0.20 m tall ridges with a furrow along the bin centerline to simulate a potential erosion control at the CDF. The other bin was left with an undisturbed, flat surface to undergo natural weathering. Volunteer plants did not grow on either bin. The sediment depth in the ridged bin was 0.6 m to allow for simulated tillage ridges, whereas the sediment depth in the flat bin was 0.3 m. Each bin wall extended 0.23 m above the sediment to reduce splash-out during precipitation events.

A rain gauge was installed at the sediment bin site. Other daily weather variables including both maximum and minimum air and 50 mm soil temperatures, precipitation, and relative humidity were obtained from an automated weather station located at a distance of about 1.5 km at the Kansas State Univ. Agronomy farm. The bins were placed on a slope of approximately 1%. Sediment characteristics related to wind erodibility were measured from September 2003 through May 2005.

Overview of Sediment Bin Data Collection

Sediment bin data elements and their sampling frequency are summarized in Table 1.

Sediment wind erodibility was measured by the following parameters: Abrasion and stability tests measured the breakdown rate of immobile sediment to mobile size in response to impacts by saltating aggregates. Sieving tests and collection of loose erodible mass on the crust were used to estimate the mobile material available to initiate wind erosion and help sustain it. The other tests were used to characterize the sediment and the driving forces causing changes in sediment wind erodibility.

Selection of Confined Disposal Facility Final Design and Its Operation

Six alternative designs were investigated for differences in volatilization losses, particulate losses, and costs (Estes et al. 2003). The six alternatives included two different disposal options (annual disposal versus biannual disposal), two different CDF configurations (one storage cell versus two storage cells), and two different dewatering options (medium dewatering effort without surface trenching for single cells and both a medium and a high dewatering effort using interior trenching for the two-cell configuration). Of these alternatives, annual disposal alternating placement in two storage cells with a medium level of dewatering effort was selected as the final operational design. This design tends to maximize the duration of surface wetness to control particulate emissions and still meet other desirable criteria, such as sediment consolidation, during the disposal process. Only operational details of the final design will be discussed.

The disposal area in the CDF will consist of two storage cells separated by dikes, as illustrated in Fig. 2. The initial dikes enclosing each cell will be about 6 m high. During the dredging

Table 1. Summary of Sediment Measurements

Measurements	Frequency	Method and reference
Dispersed size distribution	Fall, years 1, 2	Pipette method (NRCS 1996)
Coefficient of linear extensibility	Fall, years 1, 2	Dimension change (NRCS 1996)
Dry aggregate density	Fall, years 1, 2	GeoPyc envelope vol. (Micromeritics 1996)
Abrasion tests	Fall, years 1, 2	Lab apparatus (Hagen et al. 1995)
Water retention characteristic	Fall, years 1, 2	Pressure-plate (NRCS 1996)
Water drop penetration	Fall, years 1, 2	Penetration test (Bisdom et al. 1993)
Dry aggregate size distribution (tilled)	Monthly	Sieving test (Lyles et al. 1970)
Dry stability (tilled)	Monthly	Crushing energy (Skidmore and Layton 1992)
Loose erodible mass (smooth)	Monthly	Sweep with brush
Dry crust stability (smooth)	Monthly	Crushing energy (Skidmore and Layton 1992)
Soil water content	Weekly	Gravimetric sampling

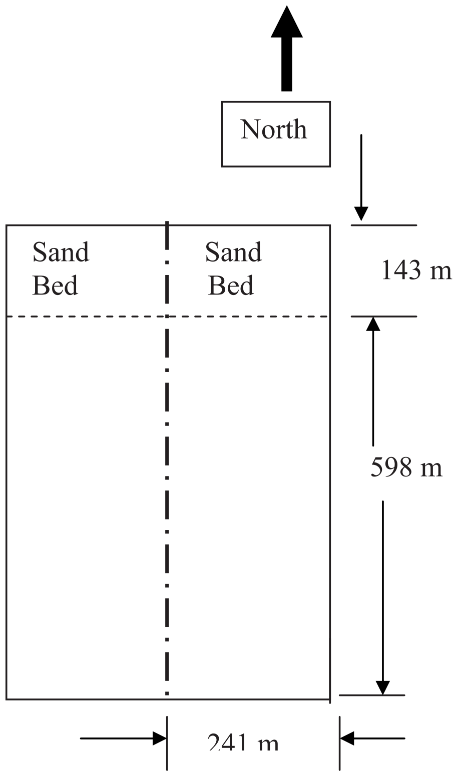


Fig. 2. Schematic of CDF with two sediment storage cells

season (May 1–September 1), slurry consisting of 1 part sediment and about 5 parts carrier water will be pumped into the north end of a cell, and the sediment will settle as the flow drains southward. Water will be decanted from the south end and recirculated to the dredging operation for use as carrier water. Because the sand settles most rapidly, a sand bed will be created at the north end of each cell. At the end of the dredging season, the water will be slowly decanted from the cell over a period of about a month and then treated prior to disposal. After dewatering, the resultant surface will be smooth, but shrinkage cracks will open as the surface dries. Dredged material placement will alternate annually between the two storage cells; therefore, the surface soil moisture cycle is 2 years in length.

Simulation of Saturated Surface Sediment Using PSDDF and HELP Models

For the final operational design, the surface conditions of the dredged material in the CDF were predicted by modeling the consolidation and desiccation of a lift of dredged material in a partially filled CDF using the USACE Primary Consolidation, Secondary Compression and Desiccation of Dredged Fill (PSDDF) model (Stark et al. 2005a,b). Application, validation, and calibration of the PSDDF model have been accomplished at many sites using comparisons of measured and predicted components over a range of conditions (Stark et al. 2005b; Pizzuto and Poindexter-Rollings 1989; Myers et al. 1993). Surface moisture is a strong function of the dredged material settlement expelling water to the surface materials, as well as infiltration of precipitation and desiccation of soil water.

The PSDDF model is a one-dimensional nonlinear numerical model to predict the large strain settlement of fine-grained dredged material and/or underlying compressible foundation materials that may be over-, under-, or normally consolidated. The most important natural processes affecting the long-term settlement, and thus, service life of dredged material placement areas are primary consolidation and desiccation. Nonlinear finite strain consolidation theory is used to predict the settlement due to self-weight and surcharge-induced consolidation. An empirical desiccation model is used to describe the settlement caused by removal of water from confined dredged material by surface drying, considering precipitation, runoff, evaporation, and crusting (Stark et al. 2005a).

Runoff and evaporation input for the PSDDF model was generated using the U.S. Environmental Protection Agency (EPA) Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1994a,b). The HELP model is a water-balance model developed to predict monthly and annual estimates of the hydrologic components. Verification of the HELP model has been performed at many sites using comparisons of measured and predicted water-balance components over a range of conditions (Peyton and Schroeder 1988). The model employed a description of the CDF profile, dredged material soil moisture retention characteristics, representative daily precipitation, temperature, and solar radiation data for the site, and other characteristic climate data to predict mean monthly PSDDF input for evaporation and precipitation, as well as long-term runoff efficiency.

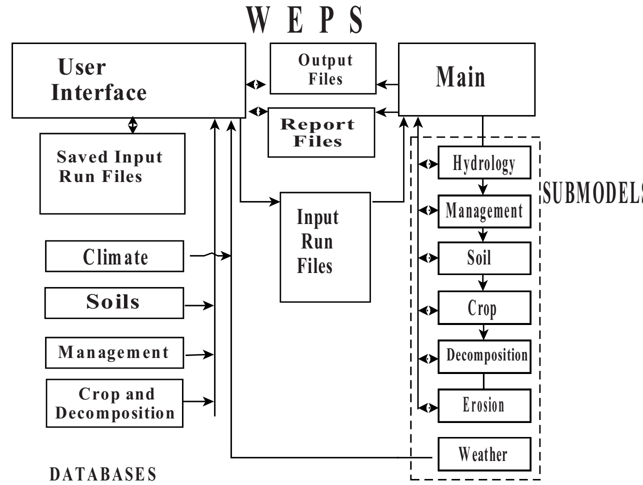


Fig. 3. Schematic of databases, submodels, and interface of the WEPS simulation model

Simulation of Particulate Emissions Using the WEPS Model

The WEPS is a process-based, daily time-step model that simulates weather, field conditions, and wind erosion on croplands. The WEPS is modular in structure and includes a weather simulator and five submodels that simulate surface conditions on a daily basis of crop growth, residue decomposition, soil aggregate/crust status, hydrology, and management (Fig. 3) (Hagen 1991; Wagner 1996).

When wind speed exceeds the threshold for erosion, the erosion submodel simulates erosion on a subhourly basis. Particulate emissions (<0.10 mm diameter) are generated by three mechanisms during wind erosion—direct entrainment of loose aggregates, abrasion from immobile clods/crust, and breakage of mobile saltation/creep-size aggregates (Hagen et al. 1999; Mirzamostafa et al. 1998). The WEPS simulates emissions from all of

Table 2. Conditions Simulated for Two-Cell Scenario

Treatments	Barrier or dike heights (m) North	South	East and west	Erodible cell dimensions (m) East–West	North–South	Number of weather sets
Base	0.6	1.8	1.2	241	598	3
Stablized	0.6	3.7	3.0	241	598	3
Sand bed	0.6	5.5	4.9	241	598	3
Snow fence	1.2	1.2	1.2	241	30	3
1.22 m tall	1.2	1.2	3.0	241	30	3
60% porous	1.2	1.2	4.9	241	30	3
Barriers	0.5	0.5	1.2	241	30	3
0.46 m tall	0.5	0.5	3.0	241	30	3
0% porous	0.5	0.5	4.9	241	30	3
Stabilized	0.6	1.8	1.2	241	239	3
Strips 60%	0.6	3.7	3.0	241	239	3
Cover	0.6	5.5	4.9	241	239	3
Mulched	0.6	1.8	1.2	241	598	3
Vegetation	0.6	3.7	3.0	241	598	3
100% cover	0.6	5.5	4.9	241	598	3
4.6 m strips	0.6	1.8	1.2	241	30	3
Mulched	0.6	3.7	3.0	241	30	3
Vegetation 30% cover	0.6	5.5	4.9	241	30	3

these sources. It also simulates the portion of emitted particulates less than 10 μm in diameter (PM10). The wind speed reduction of the dikes surrounding the CDF cells was also simulated in the WEPS.

Validation of the WEPS has been accomplished using comparisons of measured (Fryrear et al. 1991) and predicted soil loss for daily windstorms over a range of bare soil surfaces (Hagen 2002). The sediment generation and transport equations used in the model (Hagen et al. 1999) as well as additional information about the model can be found on the internet (Wagner 2007). In these simulations we assumed the sediment would be subject to potential wind erosion only during periods when the HELP and PSDDF models predicted the surface was not saturated.

An air registration with the Indiana Dept. of Environmental Management requires that the particulate emissions from the CDF site must not exceed 22.7 Mg/year. Thus, in addition to a base configuration of the CDF, the USACE requested that a number of potential wind erosion control practices be included in the simulation of emissions of suspension-size particulates (<0.10 mm diameter) that might exit the CDF. We assumed any moving saltation and creep-size aggregates would be trapped within the cells in the sheltered area created by the surrounding dikes.

Blowing sand from the sand beds impacting the crusted downwind surface would likely increase emissions well above the tolerable level. Hence, in the base case for these simulations, we also assumed that any erosion from the sand beds would be controlled, so the sand would not impact the remaining cell surface.

WEPS Input Parameters for Particulate Emission Estimates

For the simulation runs, configuration dimensions were assigned for the two cell scenarios (Table 2). In the base scenario, the erodible areas were assumed to be the cell area reduced by the area of the stabilized sand bed. The sand bed was assumed to provide some degree of shelter and was estimated to be about 0.6 m higher than the erodible surface at the north end of each erodible cell area.

In addition to the base scenario, several potential erosion controls were simulated. Snow fence spaced at 30 m intervals in an east–west orientation was one of those control systems. Fences, 1.2 m tall, with 60% porosity were selected as representative of wind breaks that shelter significant areas from wind erosion. A second class of control methods does not shelter significant area from the wind but rather traps saltation-size aggregates so they cannot continue to abrade the downwind crusted area. This class was simulated as 0.45 m tall barriers, oriented in the east–west direction and spaced at 30 m intervals.

Another potential wind erosion control method is to use a soil stabilizer to provide an immobile crust on the surface. With 100% coverage, the stabilizer should be totally effective. To minimize the amount of stabilizer, we assumed the stabilizer would be applied to the smooth surface in strips oriented east–west across the surface, and would cover 60% of the surface. Further, we assumed the stabilizer would not trap abrader from unprotected upwind strips or contribute any additional abrader to the air stream. In this case, the stabilizer merely acts to stabilize the surface area to which it is applied and reduce the overall size of the erodible area.

Tests of vegetation germination on the sediments showed that a hydro-mulch was needed to ensure successful grass germination and growth (R. Price, personal communication, 2005). Hence, erosion control with grass seeded in hydro-mulch was simulated for 100% coverage assuming that 100% of the base case area might erode even with vegetation cover. However, the vegetated area did not erode. Hence, when simulating 4.6 m wide strips oriented east–west that covered 30% of the base case erodible area only the nonvegetated area was considered erodible.

Sediment texture has been reported as silty sand in the Unified Soil Classification System (USAED 2000), but settling of the sand at the north end of the cells will further enrich the silt and clay fraction of the erodible area. To capture these effects in the simulations, we used primary particle size fractions of dispersed sediment as 18% clay (<0.002 mm), 42% silt (0.002–0.050 mm), and 40% sand (>0.050 mm). Because the sediments will be placed hydraulically, data collected mainly from the flat sediment bin were used to modify other input variables in the WEPS. For similar weather events at Manhattan, Kan. and the CDF, we assumed that sediment wind erodibility response measured at Manhattan, Kan. would also occur at the CDF. The weather sets used in the simulations are described in the following.

Input Parameters for Weather Simulation

Long-duration weather records were not available at the CDF site. Hence, to estimate likely long-term emissions from the CDF, three weather sets were developed using three climate stations and three nearby stations with suitable wind records (Table 3). The average annual emissions from the three sets were averaged and are reported in the section entitled "Results and Discussion." A 5-year weather record near the CDF site was supplied by EPA personnel (T. Ramaly, personal communication, 2004) for use in estimating the emissions. These data were run twice for a total of 10 years so all 5 years of weather data were applied to every year of the 2-year operational cycle. For the other two weather sets, the daily weather variables were simulated using the CLIGEN

Table 3. Climate and Wind Data Sets Used for Simulation Analyses

Station	Weather set	Latitude	Longitude	Number of years in database	Number of years simulated
Chicago Weather Bureau Airport	1	41.78	87.75	65	20
Chicago University	2	41.78	87.60	45	20
Measured Weather (EPA)	3	41.67 secondary 41.64	87.51 secondary 87.49	5 (1987–1991)	10 10
Chicago O'Hear Airport	1	41.59	87.54	44	20
Chicago, Midway Airport	2	41.47	87.45	28	20
Measured Weather (EPA)	3	41.65 secondary 41.64	87.51 secondary 87.49	5 (1987–1991)	10

weather simulator by inputting monthly weather statistics from databases that summarized records for the Chicago WB Airport and Chicago Univ.

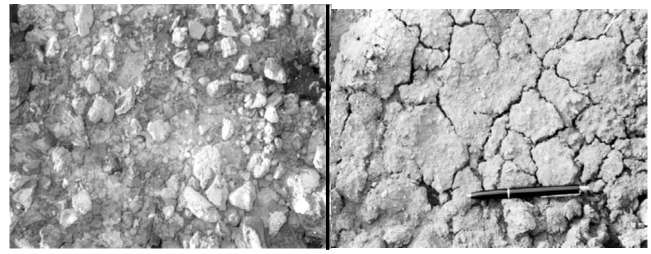
The hourly wind speeds were simulated using the WINDGEN wind simulator by inputting monthly wind statistics from databases that summarized data for O'Hare Field, Chicago, and Chicago/Midway. The simulations were run for 20 years for the 2-year cell operational cycle. This resulted in 10 years of weather simulation for each year of a cycle.

The WEPS model currently simulates wind speeds without correlation to precipitation events. If high wind events in the Chicago area are highly correlated with the precipitation events, the WEPS will overestimate the emissions, because the surfaces would be wet during the highest wind events. Analyses of data in the real weather supplied by the EPA showed wind speeds did not exceed 20 m s^{-1} on days without precipitation. Hence, maximum wind speeds in the simulated data were reduced to 20 m s^{-1} for the simulation runs.

Results and Discussion

Intrinsic and Temporal Properties of Dried Sediments

A number of characteristics of the CDF sediment were measured in the laboratory (Table 4). The bulk sediment texture is sandy loam in the USDA soil classification system, but close to a loam. Because clay content was low, the coefficient of linear extensibility (COLE) obtained by rewetting dried sediment clods was relatively low. Because of the low COLE, cracks created upon drying did not close completely when precipitation rewetted the surface. Aggregate density was low, but water retention measurements at less than 1.5 MPa were high compared to typical observations for mineral soils.



(a) (b)

Fig. 4. Flat sediment surface with clods in September, 2003 (a) and with crust in December, 2003 (b)

The flat surface was initially armored with immobile clods with small amounts of erodible-size material on the surface among the clods (Fig. 4, left-hand side). There were a number of small precipitation events during the fall and early winter that transformed the flat surface from clods to a crusted surface (Fig. 4, right-hand side). The initial precipitation had little effect on the amount of erodible (<0.84 mm diameter) sediment (Fig. 5), and the surface was very resistant to erosion. Numerous freeze–thaw cycles coupled with wet/dry cycling sharply increased the erodible fraction (<0.84 mm) at the surface during both winter periods (Fig. 5).

A water-drop penetration test (Bisdom et al. 1993) showed that after initial drying, the surface sediment was moderately water repellent. Hence, precipitation on the ridged surface tended to quickly run off. Both the cracks and large aggregates tended to persist in the ridged bin through December. Erodible-size soil created by weathering of the ridges tended to collect in the furrow and also move down the cracks. Aggregates on the ridged surface tended to remain larger (Fig. 6) and have lower coefficients of abrasion (Fig. 7) than the flat surface throughout the test period. However, weathering processes significantly increased the erodible fraction on the ridges by the second winter. The 4% oil and grease content of the sediment reported by USACE likely contributed to the water repellency that was observed.

Abrasion susceptibility of immobile aggregates and crust is indicated by the coefficient of abrasion. This was measured by a crushing energy meter and also directly by a few wind tunnel abrasion tests. A polynomial equation fitted to these data also revealed a strong cyclic response to the seasonal weather varia-

Table 4. Means and Standard Deviations of Four or More Replications of Measured Sediment Characteristics

Measured characteristic	Parameter	Parameter	Parameter	Parameter
Dispersed particles	Sand	Silt	Clay	
Size distribution (%)	53.9 ± 2.4	37.2 ± 1.8	8.9 ± 1.1	
Coefficient of linear extensibility	0.0072 ± 0.0013			
Dry aggregate sizes	Diameter 2–4 mm	Diameter 4–6 mm		
Density (mg m^{-3})	1.26 ± 0.09	1.20 ± 0.07		
Water test suctions	0.001 MPa	0.006 MPa	0.033 MPa	1.5 MPa
Water retention (%)	45.5 ± 2.6	43.5 ± 0.4	37.9 ± 0.3	7.4 ± 2.3

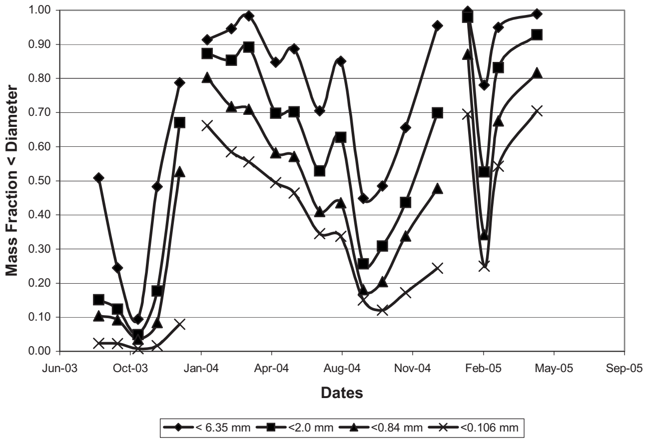


Fig. 5. Monthly cumulative mass fractions less than given aggregate size in near-surface sediment on flat bin

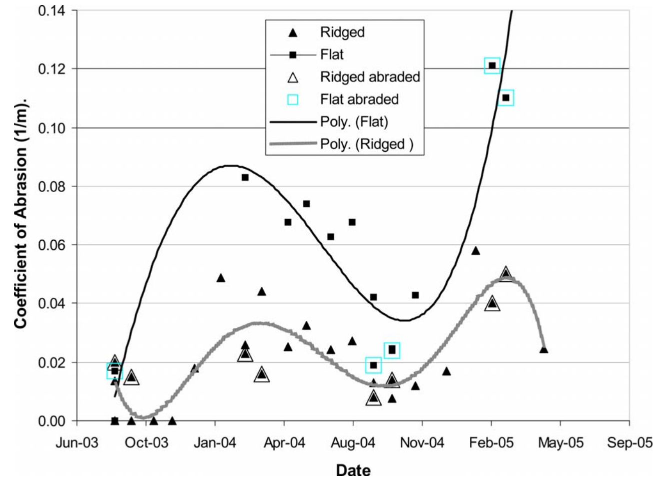


Fig. 7. Cyclic variations in dry aggregate stability represented by coefficient of abrasion (m^{-1}) of immobile clods and crust. Coefficients of abrasion measured by crushing energy meter (CE) or direct wind tunnel abrasion by saltating sand (WT). Polynomial equations fitted to flat (R^2=0.68) and ridged (R^2=0.86) data.

tions (Fig. 7). Thus, saltating aggregates traversing 1 m of immobile surface sediments create additional mobile sediment that is proportional to the product of their mass and the coefficient of abrasion.

Later, wetting coupled with freeze/thaw and drying cycles weakened the crust structure and increased the loose soil on the crust (Fig. 8). On the flat surface, a shallow frozen subsurface layer tended to trap precipitation near the surface, so the breakdown of the sediment structure was more severe than on the ridged surface. Polynomial equations fitted to the data reveal sediment structure varied in a cyclic pattern with a decrease in erodibility in the summer (Figs. 5–8). As sediment structure weakened, more erodible material passed the 0.84 mm sieve and the loose material on the crust increased.

Although the seasonal trends are clear, there were rapid changes in the amount of loose material within seasonal patterns. For example, loose sediment on the crust became negligible when the crust dried after a snow melt in January 2005.

In general, erodibility increased in winter and spring followed by a decrease in summer. The decreased erodibility in summer is likely caused by increased "glue" from microbial activity and the absence of freezing forces. However, the summer erodibility still remained above the values that occurred upon initial drying of the sediment. The ridged bin remained relatively resistant to erosion because clods armored the ridges, and the erodible sediment created during the freeze/thaw cycles moved to the furrow and also down the large cracks in the surface. However, the structure of even the immobile ridge aggregates became weak by spring in year two of the observations. The surface in the flat bin generally remained crusted and resistant to erosion until the freeze/thaw cycles weakened the crust and increased the loose, erodible-size surface aggregates to make the surface moderately erodible.

Consolidation of CDF Saturated Sediment Using HELP and PSDDF Models

Disposal of dredged material as a hydraulically placed slurry begins in May and ends in August. After placement of a lift is completed, excess carrier water is decanted from the CDF cell for another month. The initial dredged material lift thickness was predicted to be 1.3 m with an initial void ratio of 5.4 or a porosity of 0.84 at the end of August based on the project conditions and

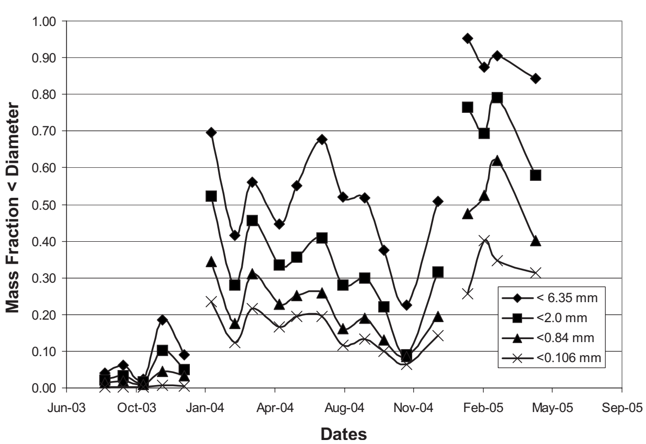


Fig. 6. Monthly cumulative mass fractions less than given aggregate size in near-surface sediment on ridged bin

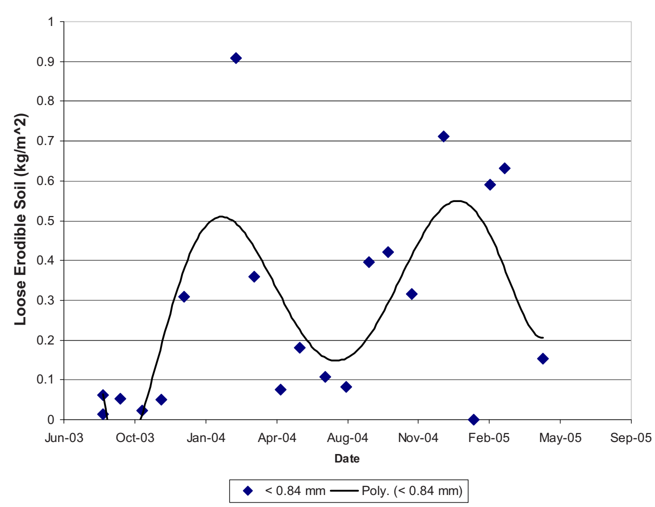


Fig. 8. Cyclic variations of loose, erodible surface sediment on flat bin. Polynomial equation (R^2=0.72) fitted to data.

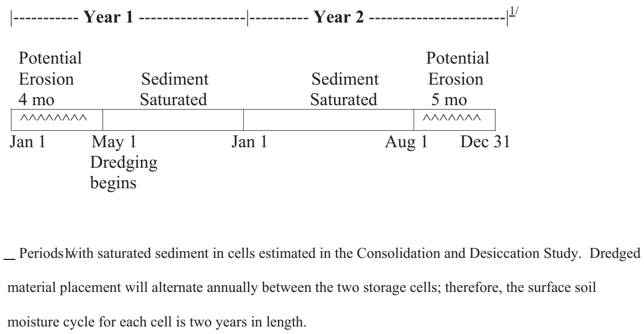


Fig. 9. Schedule of dredging, dewatering, and potential erosion periods for the planned CDF operations on a single cell in the two-cell configuration

settling characteristics. At this point desiccation from the saturated dredged material can start; however, the water from settlement and precipitation exceeds the rate of evaporation throughout the first fall, winter, and spring following placement. When the evaporation plus runoff exceeds the rate of precipitation plus pore water expulsion, the surface material loses saturation and crust starts to form. Under average conditions, crust formation is predicted to start at the beginning of the following August, approximately 1 year after placement is completed as shown in Fig. 9. After 1 year of consolidation, the lift of dredged material is predicted to have undergone about 0.5 m of settlement (about 85% consolidated). The surface is predicted to remain crusted until the following May, when the next lift of dredged material is placed in the cell. Once crust starts to form, an additional 0.15 m of settlement occurs (about 0.06 m due to desiccation), forming about 0.1 m of crust. These simulations showed that the surface may not be saturated and wind erosion could occur during 9 months in the 2-year cycle (Fig. 9).

Estimated Particulate Emissions Using the WEPS Model

For the base scenario with a stabilized sand bed, emissions ranged from 1.34 to 3.44 Mg/ha (Table 5). As cells are filled, the dike heights decrease and this in turn decreases the sheltered area and increases emissions. The emission values are small and occur during brief periods when the surface is dry enough to erode. Small amounts of suspended emissions are difficult to prevent on large, smooth surfaces. The major reason is that any saltating aggregates will travel long distances, impact the surface numerous times, and create suspended sediment with each impact. Hence, applying some level of erosion control may be necessary to maintain emissions below the permitted level of 22.7 Mg year^{-1} for the CDF site.

All the simulated erosion control systems provided substantial reduction in the potential erosion. Snow fence spaced at 30 m intervals with 60% porosity was selected as a typical control, but snow fences with 40% porosity or with greater height would provide somewhat more sheltered area than the simulated fence.

Control methods that trap saltation-size aggregates, but do not shelter significant surface area from wind stress, are represented by the 0.45 m tall barriers. These were also oriented in the east–west direction and spaced at 30 m intervals. Trenches or stabilized tillage ridges could also be used as alternative methods to trap saltating aggregates.

Table 5. Results of the WEPS Simulation of Potential Suspension-Size CDF Particulate Emissions from Two Cells with Annual Dredging to Alternate Cells with Emissions Averaged for Three Weather Sets

Scenario: Two cell treatments	Cell fill level	Annual (Mg/ha)	Erodible area (ha)	Annual total loss (Mg)
Base	Full	3.44	28.77	98.9
Stabilized	Medium	2.11	28.77	60.8
Sand bed	Low	1.34	28.77	38.6
Snow fence	Full	0.22	28.77	6.4
1.22 m tall	Medium	0.11	28.77	3.2
60% porous	Low	0.04	28.77	1.3
Barriers	Full	0.26	28.77	7.4
0.46 m tall	Medium	0.11	28.77	3.2
0% porous	Low	0.04	28.77	1.3
Stabilized	Full	1.26	11.49	14.5
Strips 60%	Medium	0.71	11.49	8.2
Cover	Low	0.36	11.49	4.1
Mulched	Full	0.00	28.77	0
Vegetation	Medium	0.00	28.77	0
100% cover	Low	0.00	28.77	0
4.6 m strips	Full	0.20	25.05	5.0
Mulched	Medium	0.09	25.05	2.3
Vegetation	Low	0.04	25.05	0.9

A soil stabilizer provides an immobile crust on the surface. When properly applied with 100% coverage, the stabilizer should be totally effective. When simulating partial stabilizer cover, we assumed the stabilizer would not trap abrader from unprotected upwind strips or contribute any significant saltating or suspended aggregates to the air stream. Hence, the stabilizer merely acted to stabilize the surface area to which it was applied and thereby reduced the overall size of the erodible area. If stabilizer were applied to a ridged surface that also provided a trap for saltating aggregates, it could function similarly to the vegetative strips and stabilizer coverage could be reduced to 13% of the base cell area.

Because experimental cloddy ridges in the sediment bins were relatively stable for a significant period, one might use them as a primary erosion control and only add stabilizer if weathering caused them to became unstable.

Vegetation was also simulated as a control measure. The mean and standard deviation of the simulated above-ground biomass of grass production on the cell surfaces using the three weather sets are shown in Table 6. Grass was planted in the late summer or fall of the first year of the cycle after dredging ceased as suggested by R. Price (personal communication, 2005). Lack of sunshine and warm temperatures on the late-planted grass resulted in low production of biomass in the first year. Nevertheless, erosion was controlled by 100% vegetation coverage of the cells (Table 5). Although not simulated, the hydro-mulch would also contribute to surface stability.

In the second year of the cycle, biomass production was larger than during the first year because growth occurred throughout the summer. The simulated biomass ranged from 28 to 1216 kg/ha after 6 weeks of growth. The simulated production was in reasonable agreement with results from pot studies (R. Price, personal communication, 2005). In the pot studies, measured biomass ranged from 245 to 817 kg/ha after 6 weeks of grass growth on Indiana Harbor sediments. It is unclear if the biomass production can reach the year-end values predicted in the second year. Nev-

Table 6. WEPS Model Simulation of Grass Biomass Production during 2 Years

Scenario	Cycle year	Date: seeded or begin growth	Simulated 6 week biomass (kg/ha)	6 week effective SAI (m^2/m^2)	Simulated year end biomass (kg/ha)	Year end effective SAI (m^2/m^2)
Two cell	1	Sep. 3	28 ± 4	0.00	28 ± 4	0.00
Two cell	2	Jul. 3	$1{,}216 \pm 163$	0.37	$2{,}160 \pm 195$	0.70

ertheless, erosion in both the fall and following spring was controlled by 100% vegetation coverage of the cells.

In the initial simulations, the grass appeared to stabilize the surface. Further, the predicted silhouette area indices (SAI) of 0.37 before fall in the second year would also be capable of trapping small amounts of saltating aggregates. Hence, 4.5 m wide grass strips spaced at 30 m intervals were simulated with only the area between strips considered erodible. The grass strips were about as effective as the other erosion control measures. The simulated erosion control measures were all effective in reducing potential erosion in the two-cell scenario.

Summary and Conclusions

A composite sample of contaminated sediment from Indiana Harbor was placed in sediment bins at Manhattan, Kan. and variations in sediment wind erodibility parameters were determined over a 22 month period. Upon initial drying, the surface sediment was stable with large cracks and had only low amounts of mobile particulates. In general, sediment erodibility increased with freeze/thaw cycling, but decreased during the summer. The ridged sediment surface maintained lower erodibility than the flat surface.

Sediment consolidation and duration of sediment saturation in the CDF cells were simulated using the HELP and PSDDF models. For the unsaturated period, the WEPS model was used to estimate potential suspended particulate emissions from the Indiana Harbor CDF. WEPS inputs included both measured and simulated daily weather and hourly wind speeds from the Chicago area, along with sediment erodibility data from the sediment bins. A CDF operational scenario using two storage cells was simulated. The hydraulic placement of the sediments in the cells results in a sand bed at the north end of the cells that needs to be stabilized to prevent abrasion of the downwind area. Even with the sand bed stabilized, the simulation results showed that some level of additional erosion control may be needed to control suspended wind erosion emissions. Snow fences, short barriers, and stabilized strips were simulated as potential erosion controls. The results showed applying any of these could provide adequate reductions in emissions to meet the target emission levels of the CDF.

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