A Predictive Model for
Sediment Transport at the
Portland Disposal Site, Maine

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A numerical model, used to predict the long term fate of sediments (LTFATE), was applied to assess the potential stability of sediment caps at the Portland Disposal Site, Maine. The modeling was performed by the Coastal and Hydraulics Laboratory of the U.S. Army Corps of Engineers, Waterways Experiment Station for the New England District.

The results showed that a cap of 50-100 cm thick, composed of sediments similar to those used in the model, would provide protection for the capped sediments even under extreme wave conditions of 14.8 m (48 ft). Using conservative parameters, the model predicted erosion from such waves might remove 11-22 cm of a cap. Thus, capped sediments (under a 50-100 cm cap) are not likely to be at risk of erosion and would remain within the disposal mound.

Depending on the characteristics of the sediments chosen as cap material, actual site losses could be significantly lower than model estimates. Therefore, once a sediment is chosen for cap material, laboratory and field experiments should be performed to determine the erosion potential for these sediments. In addition, further monitoring of the PDS to measure on- and off-site sediment concentrations, bottom roughness, and near bottom hydrodynamics would increase model accuracy. Other factors not accounted for in this modeling effort, such as estimates of sediments transported to and possibly deposited at the PDS, would tend to further reduce the estimate of actual erosion.

Model calibration was accomplished using data provided from a field sampling array that was deployed during events with waves ranging up to 5.4 m (17.7 ft) in height. Severe historical wave conditions were determined through the use of the Wave Information Study (WIS) hindcast for the Atlantic Coast and the ADCIRC ocean circulation model. This included custom refinement of the ADCIRC model grid in the New England region to provide more accurate predictions..

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# A PREDICTIVE MODEL FOR SEDIMENT TRANSPORT AT THE PORTLAND DISPOSAL SITE, MAINE

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## EXECUTIVE SUMMARY


A numerical model, used to predict the long term fate of sediments (LTFATE), was applied to assess the potential stability of sediment caps at the Portland Disposal Site, Maine. The modeling was performed by the Coastal and Hydraulics Laboratory of the U.S. Army Corps of Engineers, Waterways Experiment Station for the New England District.

The results showed that a cap of 50-100 cm thick, composed of sediments similar to those used in the model, would provide protection for the capped sediments even under extreme wave conditions of 14.8 m (48 ft). Using conservative parameters, the model predicted erosion from such waves might remove 11-22 cm of a cap. Thus, capped sediments (under a 50-100 cm cap) are not likely to be at risk of erosion and would remain within the disposal mound.

Depending on the characteristics of the sediments chosen as cap material, actual site losses could be significantly lower than model estimates. Therefore, once a sediment is chosen for cap material, laboratory and field experiments should be performed to determine the erosion potential for these sediments. In addition, further monitoring of the PDS to measure on- and off-site sediment concentrations, bottom roughness, and near bottom hydrodynamics would increase model accuracy. Other factors not accounted for in this modeling effort, such as estimates of sediments transported to and possibly deposited at the PDS, would tend to further reduce the estimate of actual erosion.

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# 1.0 INTRODUCTION

The USACE New England District (NAE) is currently analyzing resuspension potential of sediments at the Portland Disposal Site (PDS). This site is used for placement of both contaminated and clean sediments removed as part of maintenance dredging of Portland Harbor, Maine. To effectively manage the site, NAE must determine if the placed sediments are stable, i.e., do they remain essentially in place under severe weather conditions. An understanding of the resuspension potential of these sediments as well as any proposed cap is necessary before decisions can be made concerning future sediment placement or cap design. The Long Term FATE (LTFATE) model (Scheffner, 1996) has been modified and applied to the PDS to assist in predicting the stability of the placed sediments. This study is one component of the capping investigations being conducted by NAE. Sediments at the PDS lie in water depths from 40 m to 70+ m. The site is characterized by rough bottom terrain, and is exposed to unlimited fetch from the east to the south. Because of this exposure, the PDS is directly impacted by both tropical and extra-tropical wave events causing bottom sediments to experience significant wave generated shear stresses. It will be shown that under normal conditions the site is stable, but despite these depths, storm waves from low frequency (long return period) events have potential to cause moderate erosion that needs to be factored into cap design and monitoring.

LTFATE is a disposal site-analysis program that uses coupled two-dimensional hydrodynamic, sediment transport, and bathymetry change sub-models to compute site stability over time as a function of local waves, currents, bathymetry, and sediment characteristics. LTFATE was developed to simulate the long-term fate and stability of dredged material placed in open water with an initial intended use for classifying existing or proposed disposal sites as dispersive or nondispersive. The model estimates the site stability for time periods ranging from days (for storm events) to years (for ambient conditions). If the site is demonstrated to be dispersive, model output will provide an estimate of the temporal and spatial fate of the majority of eroded coarse-grain cohesionless material. The ultimate fate of the majority of fine-grain cohesive material is not estimated by LTFATE because these sediments can disperse over a large area beyond the boundaries of the localized LTFATE model. LTFATE will, however, estimate the local deposition of these cohesive sediments but this will usually be only a small fraction of the total amount resuspended from the site. The prediction of fine-grain sediment transport is further complicated, as will be described later, by the significant variation in erosion rates with depth below the sediment/water interface when compared to coarse-grain sands which erode at relatively consistent rates with variation in depth.

Wave data necessary for these applications are derived from the Wave Information Study (WIS) hindcast for the Atlantic Coast (Brooks and Brandon, 1995). An outline of derivation of specific LTFATE inputs is included later in this text. Tidal current and tidal elevation data necessary for boundary condition inputs to LTFATE simulations are developed using the ADCIRC ocean circulation model. The ADCIRC model is described in Luettich et al. (1992), the database of tidal elevations and currents for the east coast, Gulf of Mexico, and Caribbean Sea are described in Westerink et al. (1993), and the database of tropical storm surge and current hydrographs is reported in Scheffner et al. (1992). The ADCIRC east coast grid (Figure 1a) was refined (resolution increased) in the region near New England so it could more accurately predict currents and elevations at the PDS. Figure 1b shows the ADCIRC grid detail near the PDS.

LTFATE has the capability of simulating both non-cohesive and cohesive sediment transport. In addition, consolidation of cohesive sediments is accounted for to more accurately predict physical processes which occur at the site. Many sediment transport equations require near bottom velocities, but the methods incorporated in LTFATE were developed and work well using vertically averaged velocity of flow reflective of conditions outside the wave and current boundary layers. Unlike near-bottom velocities, vertically averaged velocities are not significantly effected by bottom roughness. This is an advantage in regions where bottom roughness is unknown or continually changing (however, as will be described later, uncertainties in the bed roughness estimates will contribute to uncertainties in erosion rates). Following are sections describing the effects of waves on the sediment/water interface, non-cohesive sediment transport, cohesive sediment transport, and application of LTFATE to the PDS.

## 1.1 Effect of Waves at Sediment/Water Interface

Most non-cohesive sediment transport equations are developed for a current only environment. Areas of interest where LTFATE is applied normally include bottom stresses due to both currents and waves. Therefore the effects of waves must be included in estimating sediment transport. A modification of the transport equations proposed by Bijker (1971) is incorporated into LTFATE to reflect an increase in the transport rate if the ambient currents are accompanied by surface waves. The modification, in the form of an effective increase in the depth-averaged current velocity used to compute sediment transport, is based on equations reported by Swart (1976). This increased velocity can be thought of as the current velocity that would produce a bottom stress equivalent to the stress due to the combined effects of ambient currents and waves. The effective increase in velocity for currents accompanied by waves $V_{wc}$, is written as a function of the current velocity $V_c$ in the absence of waves as follows:

$$V_{wc} = V_c \left[ 1.0 + \frac{1}{2} \left( \xi \frac{\hat{u}_0}{V} \right)^2 \right]^{1/2} \qquad (1)$$

where:

$$\xi = \hat{C} \left( \frac{f_w}{2g} \right)^{1/2} \qquad (2)$$

$$\hat{C} = 18 \log \left( \frac{12d}{r} \right) \qquad (3)$$

$$f_w = \exp \left[ -5.977 + 5.213 \left( \frac{r}{a_0} \right) \right]^{0.194} \qquad (4)$$

$$(if \ldots f_w > 0.3, f_w = 0.3)$$

$$\hat{u}_0 = \frac{Hgk}{2\sigma} \frac{1}{\cosh(kd)} = \frac{HgkT}{4\pi} \frac{1}{\cosh(kd)} \qquad (5)$$

$$a_0 = \frac{Hgk}{2\sigma^2} \frac{1}{\cosh(kd)} = \frac{H}{2} \frac{1}{\sinh(kd)} \qquad (6)$$

where $\hat{u}_0$ is the amplitude of the orbital velocity at the bed (Van De Graff and Van Overeem 1979), computed according to linear wave theory (Ippen 1966, p 28) and $a_0$ is defined as the orbital excursion (amplitude) at the bed (Swart 1976), computed from linear wave theory (Ippen 1966, p 29). In the above, the parameter $f_w$ is defined as the bottom friction coefficient (Jonsson 1966) and $\hat{C}$ is the Chezy coefficient . The parameter r is the hydraulic bed roughness and taken to be 0.197 ft (0.06 m), (Van De Graff and Van Overeem 1979). It should be noted that the bed roughness used in these calculations are due to grain size (i.e., small horizontal scale) and bed-forms such as ripples, not bottom formations such as rocky outcrops which, as will be described later, exist at the PDS (these formations would indicate that the bottom roughness values increase significantly in rocky areas, but in general it appears that these formations are in regions of the PDS where few sediment deposits exist and therefore are not accounted for here). The terms H, k, ,$\sigma$ and T represent wave height (ft), wave number ($ft^{-1}$), angular frequency ($sec^{-1}$) and period (sec) respectively. The terms d and g represent water depth (ft) and acceleration of gravity ($ft\ sec^{-2}$) respectively. This method assumes that current and orbital velocities are oriented in the same direction which is, in general, a conservative assumption which may result in shear stresses being slightly higher.

## 1.2 Non-Cohesive Sediment Transport Model Component

The equations reported by Ackers and White (1973) were selected as the basis for the non-cohesive sediment transport modeling component. These relationships predict sediment transport primarily as a function of sediment grain size, depth, and depth averaged velocity (here the depth averaged velocity is assumed to be $V_{wc}$). The equations are applicable to uniformly graded noncohesive sediment with a grain diameter in the range of 0.04 mm to 4.0 mm (White 1972).

The Ackers-White transport equations relate sediment transport to three dimensionless quantities. The first, a nondimensional grain size $D_{gr}$ , is defined as a function of the ratio of the immersed particle weight to the viscous forces acting on the grain. The value is defined as:

$$D_{gr} = D\left[\frac{g(s-1)}{\nu^2}\right]^{1/3} \tag{7}$$

where:

D = sediment diameter (i.e., $D_{50}$), ft
g = acceleration of gravity, $ft/sec^2$
s = sediment specific gravity
v = fluid kinematic viscosity, $ft^2/sec$

The value of $D_{gr}$ is used to categorize the sediment as coarse or transitional, with the following coefficients n, m, A, and C (which are used to compute sediment transport rates) defined for the two sediment classifications:

a. Coarse sediments: $D_{gr} > 60$.

$n = 0.0$
$m = 1.50$
$A = 0.17$
$C = 0.025$

b. Transition sediments: $1.0 < D_{gr} \leq 60.0$

$$n = 1.00 - 0.56\log(D_{gr}) \tag{8}$$

$$m = \frac{9.66}{D_{gr}} + 1.34 \tag{9}$$

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{10}$$

$$\log C = 2.86\log D_{gr} - (\log D_{gr})^2 - 3.53 \tag{11}$$

The second nondimensional parameter, $F_{gr}$, represents particle mobility defined as the ratio of shear forces to the immersed sediment weight. The general form of the relationship is

$$F_{gr} = \frac{v_*^n}{\sqrt{gD(s-1)}}\left[\frac{V_{wc}}{\sqrt{32}\log\left(10\frac{d}{D}\right)}\right]^{1-n} \tag{12}$$

where $V_{wc}$ is the depth averaged velocity determined from the above described modification to the current velocity to account for the effect of waves (ft/sec), $d$ is the mean depth of flow (ft), and $v_*$ is the shear velocity (ft/sec) which can be defined from Chow (1959, p 204) as:

$$v_* = \frac{\sqrt{g}V_{wc}}{C_z} \tag{13}$$

where $C_z$ is the Chezy coefficient.

The third nondimensional parameter, $G_{gr}$, defines a sediment transport rate as a ratio of shear forces to the immersed weight multiplied by the efficiency of transport. The efficiency term is based on work needed to move the material per unit time and the total fluid power. The transport rate is written as

$$G_{gr} = \frac{Xd}{sD}\left(\frac{v_*}{V_{wc}}\right)^n \tag{14}$$

where X is a nondimensional sediment transport function in the form of mass flux per unit mass flow rate. The sediment transport rate $G_{gr}$ can be related to the mobility function $F_{gr}$ through the following relationship:

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1.0\right)^m \tag{15}$$

Equations 14 and 15 are used to solve for X as:

$$X = C\left(\frac{F_{gr}}{A} - 1.0\right)^m \frac{sD}{d}\left(\frac{V_{wc}}{V_*}\right)^n \tag{16}$$

A dimensional sediment load transport rate $Q_b$, defined in cubic feet of sediment (solids) per second per unit width can be written as:

$$Q_b = XVd \tag{17}$$

Therefore, the total sediment mixture transport, i.e., solids plus voids, is written as:

$$Q_b = \frac{Q_b}{(1-e)} \tag{18}$$

where $e$ is the porosity (ratio of void volume to total volume).

A dimensional sediment transport magnitude in volume ($ft^3$) of sediment mixture per second per unit width (ft) is finally written in the following form:

$$Q = C\left(\frac{F_{gr}}{A} - 1.0\right)^m \frac{sD}{(1-e)}\left(\frac{V_{wc}}{V_*}\right)^n V_c \tag{19}$$

Equation 19 represents sediment transport as a primary function of depth, sediment grain size, and depth-averaged velocity.

LTFATE was applied to a site just south of Mobile Bay (Alabama) and successfully predicted the movement of the Sand Island disposal mound over a 30-month period from March 1987 through August 1989 (Scheffner 1996). Mound movement was tracked using six bathymetric surveys (Hands 1991). LTFATE predictions compared favorably to these bathymetry data, offering partial verification of the methods incorporated in the model.

1.3 Cohesive Sediment Transport Model Component

An improved cohesive sediment transport model has recently (1996) been incorporated into LTFATE. The model requires bottom shear stress as input. The total bottom shear stress due to currents and waves is determined using the combined current/wave 'perceived velocity', $V_{wc}$ as described earlier in this section and bottom roughness parameters. The bottom shear stress equation, in *dynes/cm*$^2$, is:

$$\tau = \rho_w g V_{wc}^2 \Big/ C_z^2 \tag{20}$$

where $\tau$ is the total bottom shear stress due to currents and waves, $\rho_w$ is the density of water, $g$ is the acceleration of gravity, $V_{wc}$ is the perceived bottom velocity due to currents and waves, and $C_z$ is the Chezy roughness coefficient. This method of calculating the shear stress compares favorably to more complex combined current/wave approaches like Christoffersen and Jonsson (1985), generally agreeing within 20%. However, this method, like the others, is influenced by bottom roughness parameters. These parameters were not measured for the sediments of interest and the results may change significantly depending on their values. Bottom roughnesses for typical ocean sediments were used in the absence of actual data from the PDS.

The factors influencing the resistance of a cohesive sediment bed to erosion may be best described by Ariathurai and Krone (1976) as: "(1) the types of clay minerals that constitute the bed; (2) structure of the bed (which in turn depends on the environment in which the aggregates that formed the bed were deposited), time, temperature, and the rate of gel formation; (3) the chemical composition of the pore and eroding fluids; (4) stress history, i.e., the maximum overburden pressure the bed had experienced and the time at various stress levels; and (5) organic matter and its state of oxidation." It is obvious from this description that the resistance of the bed to erosion will be different not only from site to site, but also potentially with depth at a given location. Therefore, erosion potential is usually considered a site specific function of shear stress (and sometimes depth). Methods have been developed to determine erosion based on stresses, but these equations require parameters whose values are site specific. A commonly used method of relating erosion to shear stress has been incorporated into LTFATE. This method relates erosion as a function of shear stress to some exponential power. The equation for the erosion rate, $\epsilon$, in $g/cm^2/sec$ is:

$$\epsilon = A_0 \left( \frac{\tau - \tau_{cr}}{\tau_r} \right)^m \tag{21}$$

where $A_0$ and $m$ are site specific parameters which vary with depth (and are usually determined by laboratory or field experiments on the sediments of interest), $\tau$ is the shear stress due to currents and waves, $\tau_{cr}$ is the site specific critical shear stress below which no erosion occurs (assumed to vary with depth), and $\tau_r$ is a reference shear stress (assumed to be 1 $dyne/cm^2$). Most research on cohesive sediment erosion has been performed in laboratory settings at moderate shear stresses less than 20 $dynes/cm^2$ (Lavelle et al. 1984). The above described method was developed for moderate stresses. Data for high shear stresses are sparse and the experimental methods are still under development (McNeil et al. 1996). Despite limitations in the understanding of high shear bed erosion, a lot can be determined by using the moderate shear equations in high shear regions. It would appear from bathymetry measurements in high shear regions, that equation 21 can adequately simulate these conditions. The shear stresses experienced at the PDS range from low during ambient conditions to moderately high during storm events.

It should be noted that the values of the site specific parameters used in these methods can vary significantly. Experimentally determined values of $A_o$ range over several orders of magnitude from $1 \times 10^{-9}$ to $5 \times 10^{-6}$ ($g/cm^2/sec$) and $m$ ranges from 1 to 5 (Lavelle et al. 1984). The experimental range of exponent $m$ values coupled with the equation for $\tau$ demonstrate that the relationship between velocity and erosion is highly nonlinear ($\tau$ is approximately a function of $V^2$ and $\in$ is a function of $\tau^m$ resulting in $\in$ approximately a function of $V^{2m}$). Therefore, rare storm events will often produce most of the cohesive sediment erosion for a given year. This is well known to occur in many rivers, lakes and near shore environments. Some studies on San Francisco Bay sediments suggest that $m$ ranges from 1-2 for these sediments, assuming long consolidation periods (Parthenaides 1965). Higher values of $m$ are reserved for freshwater lake and river sediments. The values of $A_o$ and $\tau_{cr}$ for cohesive and mixed sand/cohesive sediments are also known to vary significantly with depth below the sediment/water interface (McNeil et al., 1996). This variation is due to the effects of aging and consolidation of the sediment layers. These effects must be accounted for when modeling the sediment bed. Choosing a single value for $A_o$ or $\tau_{cr}$ for all vertical layers of the sediment bed will result in either excessive erosion during large storms (if the values are based on the surficial sediment characteristics) or insufficient erosion during moderate events (if the values are based on deeply buried sediment characteristics). Choosing appropriate values for these parameters is essential to accurate sediment erosion prediction. Methods used for parameter selection for the PDS will be described in the next section.

## 2.0 APPLICATION OF LTFATE TO THE PDS

The PDS lies in 40-70 m of water 13 km off the coast from Portland, ME (Figure 2), and encompasses approximately 3.5 $km^2$. The site is described by McDowell and Pace (1996) as having "rocky, irregular relief composed of a complex network of bedrock outcrops, shear ridges caused by glacial scour, and small topographic depressions containing natural sedimentary deposits of gravel, sand, silt and clay". Three bathymetric surveys of the site, performed in 1976, 1989 and 1996 were available for this analysis. Each survey covered different portions of the PDS. The 1996 survey covered approximately the southern 45% of the site as well as small area surrounding the perimeter of the site. The 1976 and 1989 surveys were at nearly identical locations close to the center of the site. Data from the 1989 and 1996 surveys were combined to create the site configuration for the LTFATE simulations. These surveyed regions combined cover approximately 60% of the total PDS as well as a narrow band (<200 m wide) around the southern half of the PDS and form an inverted 'T' shaped configuration. For LTFATE simulations, this was defined as the LTFATE PDS region of interest (Figure 3a). Although this region does not cover the entire PDS, the lack of bathymetry data for the remaining portions made simulation of the entire PDS impractical. From a mound stability standpoint, the area not included is probably unimportant. The stability of a mound in the LTFATE PDS region would be only minimally effected by bathymetry variation in other regions of the PDS. It is significant to note that all areas of the PDS that have previously been used for sediment placement fall within the LTFATE PDS region.

Surrounding the LTFATE PDS region, a 125 m wide band was developed as a transition zone and the depths in this band were gradually varied from the adjacent LTFATE PDS depth to 60 m. All areas surrounding the LTFATE PDS mound and this band were assumed to be 60 m in depth. No sediment was permitted to erode from the band or 60 m depth regions. The grid for the LTFATE simulations including the PDS and surrounding regions is 129x118 cells. Each cell is 25x25 $m^2$. Figure 3a is a depth contour plot of the LTFATE PDS and surrounding regions.

The fact that the site contains many large rocky outcrops indicates that sediments can not erode from all areas of the PDS. Rather, most sand, silt and clays are confined to the deeper channel regions between these outcrops. Therefore, for all LTFATE simulations, areas within the PDS that are shallower than 55 m were assumed to be solid rock and experienced no sediment erosion (Figure 3b). A 55-60 m limit for sand, silt and clay is probably a reasonable estimate given known characteristics of the site. From this analysis, approximately 57% of the LTFATE PDS is covered with erodible material.

SAIC collected an extensive data set including near bottom (< 1 m) current velocity, wave height, wave period and turbidity (converted to TSS concentrations) from a bottom resting tripod at one site at the southwest corner of the PDS for the period February 27 to May 14, 1996 (McDowell and Pace, 1996). The turbidity data were collected hourly at 33 and 81 cm above the bottom and the current velocities were collected at 0.5 Hz intervals for a one minute period every ten minutes using an InterOcean S-4DW electromagnetic current meter (McDowell and Pace, 1996). Wave height and period data were also collected at NOAA buoy 44007 in deeper water approximately 6.4 km southwest of the PDS (Figure 2). The data collection period included nine moderate storm events, with significant wave heights ranging from 2-5 m. The data indicate elevated turbidity during seven of nine storms, with highest suspended solids concentrations occurring during the two storms with significant wave heights in excess of 3m. The near bottom average current velocities were not affected by the onset of events, but were rather consistent in magnitude for the entire period of measurement. Therefore the increased turbidity associated with events can be attributed to either the increased bottom orbital velocities at the site or sediment suspended in shallower water and advected to the site. The data indicate that peaks in concentration were associated with peak orbital velocities. This lack of a lag factor between peak orbital velocities and concentrations indicates that the increased turbidity is due to local suspension of sediments at or near the PDS (McDowell and Pace, 1996). This information is an excellent indicator for estimating the critical shear stress for the surficial sediments at and surrounding the PDS.

However, these data do not give a complete picture of surficial sediment erodibility at the PDS. Further data would be necessary for this. Because LTFATE is a localized model, calculations of TSS concentrations at the site, in this case the PDS, are heavily dependent on boundary concentrations used as model input. These data are generally acquired from a second turbidity measurement some distance (and preferably updrift) from the site. In addition, placed sediments are probably physically and chemically different from the surrounding sediments. Therefore, the two sediments would erode at different rates. The fraction of the TSS measured by the turbidity meters from placed verses natural sediments is unknown, and would be difficult to determine. It is also well known that critical shear stress for initiation of suspension varies with depth. As previously mentioned, the SAIC data set provided data for estimating the critical stresses for the uppermost layer. However, the data do not provide information concerning material below this surficial layer. A more accurate picture of the varying rates can be acquired by collecting undisturbed core samples of the sediments of interest and performing various laboratory experiments to estimate the resistance to erosion and the rates of erosion as a function of depth of burial. These data, although expensive to collect, are often used to calibrate cohesive sediment transport models like LTFATE, i.e., they are used to determine the values and change in values with depth of $\tau_{cr}$, $A_0$, and $m$ in equation 21. These erosion potential data determined from cores can also be used to quantify variation in sediment parameters between the placed and natural sediments for the area.

From the above discussion, it can be seen that the TSS data collected by SAIC are an excellent indicator of surficial layer critical shear stresses in the region near the PDS, but do not necessarily result in an accurate indication of the erosion rates of placed or natural sediments at the PDS. Therefore these data were used only to produce critical shear stresses for the surficial sediments and to serve as a general indicator of the upper bounds of erosion from the surficial sediment layer at the site. Calibration of the model using these data was further complicated by the fact that LTFATE is a two-dimensional, vertically integrated model and the data were near-bottom concentrations. Additional TSS data further up in the water column from the bed would have produced a total water column load which could be converted to vertically averaged concentration estimates for calibration of the two-dimensional model. It is, however, unlikely that TSS concentrations at mid-depth in the PDS would have been elevated during the weak to moderate storms of the SAIC data collection period. When comparing the near bottom TSS field data to model estimates of vertically averaged TSS, the model results are expected to be lower in light of this difference.

## 2.1 Model Forcing/Calibration

Hydrodynamic boundary conditions input to LTFATE include vertically averaged currents at the boundary, wave height, wave period, and tidal elevation (although in these water depths tidal elevation contributions will be negligible). The period of April 6-18, 1996, was chosen as the first period for model calibration. This period included three events (as determined by wave heights at the buoy). These events are defined as storm numbers 5, 6 and 7 by McDowell and Pace (1997). The first event, on April 8 (storm 5) included maximum significant wave heights of 3.5 m. This event was followed closely by another on April 10 (storm 6), which included maximum significant wave heights of 3.9 m. The third event, on April 16 (storm 7), was the largest with maximum significant wave heights of 5.4 m (Figure 4). Other events during the SAIC data collection period were also simulated, but the events were not as large as the April calibration period. Two LTFATE hydrodynamic input data sets were developed for this period. Both used as input the wave height and period from the buoy. Two current velocity data sets were available for LTFATE boundary condition development. The first is the data from the SAIC near bottom current meters. These data were used as the vertically averaged velocity for the first data calibration period LTFATE input data set. The second input data set was developed using results of the ADCIRC simulation of tidal currents for the same period. The two velocity inputs were similar in magnitude, generally under 15 cm/s (current meter velocities were slightly lower), but varied significantly in direction. As will be discussed later, the choice of velocity input, near bottom current meter or ADCIRC vertically averaged velocity results, had little impact on the results for total erosion from the site. Tidal elevation inputs were derived from the ADCIRC simulations. Sediment boundary condition inputs are TSS concentrations at the inflow boundaries. Since no boundary condition data were available for these simulations, all inflow boundary TSS concentrations were assumed to be zero. This may result in artificially low amounts of re-deposition of sediment at the site. The resulting bathymetry change can therefore be considered more of a gross erosion flux rather than a net flux of sediment at the sediment/water interface. The zero boundary conditions may seem unrealistic, especially during storms, but the nature of the PDS, with many rocky ridges, may block most sediment from being advected to the site from other locations if sediments are not high in the water column. Therefore the assumption of no inflow boundary concentrations can be considered a conservative assumption, i.e. assuming the worst case condition of all sediment being blocked from entering the PDS.

As a first step in choosing the appropriate sediment characteristics for the site, the field data collected during the February-May 1996 survey by SAIC at the PDS were analyzed. The sediments collected by grab sample and visually analyzed were described as a mixture of rock, gravel, sand, silt and clay (McDowell and Pace, 1996). The predominant sediment types are sand, silt and clay. The LTFATE model can not, at present, model both cohesionless (sand and coarse silt) and cohesive (silt and clay) sediments. Therefore a single sediment type needed to be chosen. To select a sediment type, events (storms) within the survey period were simulated for both cohesive and cohesionless sediments and the results compared to the TSS data collected during those periods. These experiments indicated that, if classified as cohesionless coarse silt (0.06 mm), insufficient sediment was transported to accurately reflect the SAIC measured TSS concentrations for the April 1996 events. Two relevant data sets were available to assist in determining the classification of PDS sediments for LTFATE simulations. The first was sediment size analysis of 16 cores extracted from the PDS in July, 1992. Twelve of the sixteen sediment samples were greater than 50% (by dry weight) silt and clay (U.S. Army Corps of Engineers, 1996). The second data set, sediment core samples collected during summer 1995 from 23 locations in Portland Harbor (which can be assumed to be similar to sediments placed at the PDS) and analyzed by the Army Corps (Report Number 446-50274-1), indicate that 17 of 23 core samples were greater than 50% silt and clay material. Therefore for all modeling purposes the sediments were described as fine-grain cohesive. This would seem reasonable for mixed sand/silt/clay sediments because research has indicated that sediments with even a relatively moderate fraction of silt/clay will behave more like cohesive sediments than like pure sands (for example, the erosion potential will decrease significantly with depth below the sediment/water interface). Research has demonstrated that there is a critical percent of cohesive sediment in mud/sand bed mixtures above which the muds form a network of strong chemical bonds and the bed must be treated as a cohesive sediment bed. Below this critical percent, the mixture can be treated as non-cohesive (Toorman, et al., 1995). Due to the nature of cohesive sediments, it does not take a large percent mixed with sands before the mixture starts behaving in a cohesive manner. Whitehouse, et al. (1995) reports the amount at 3-15% fines by weight, depending on the types of mud and sand in the mixture. Therefore, choosing correct parameters for the cohesive sediment equations can accurately represent a bed comprising of a significant portion of sand mixed with the silt and clay.

After selecting the type of sediment to be modeled, the appropriate parameters for the sediment erosion rate equations needed to be selected. Unfortunately the grain size distribution data (collected at the PDS and Portland Harbor) alone can not be used to further refine the erosion potential parameters in equation 21. Therefore other data were used to define erosion potential parameters. The suspended solids concentrations measured by SAIC were near bottom values. It is not possible to compare directly near bottom concentrations (field data) and vertically averaged concentrations from the model. The former tend to be much larger because the water column is not, in general, well mixed at these depths. To convert the field data to total water column load (i.e., vertically averaged concentrations) would require an understanding of the distribution of suspended sediments above this near bottom layer. However, the near bottom data do provide a qualitative understanding of conditions for which erosion occurs and a first estimate of the magnitude of erosion to compare to model output and to assist in estimating values for parameters $A_0$, $\tau_{cr}$, and $m$ in equation 21.

For application of LTFATE to the PDS, the value of exponent $m$ was set at two, a reasonable value for ocean sediments (Partheniades, 1965). The value of coefficient $A_0$ generally changes dramatically with depth, often over orders of magnitude (Ziegler and Lick, 1986). The values are larger for the surficial sediments and decrease with depth reflecting the greater resistance to erosion of the more dense, deeply buried sediments as well as the effects of sediment armoring on increased erosion resistance. Table 1 shows values of $A_0$ used for all PDS simulations. Similarly, the values of the critical shear stress, $\tau_{cr}$, increase with depth to reflect the increased resistance to erosion. The surficial layer sediments are often recently deposited and are kept in a less dense, loose state by such factors as bioturbation and the agitation of currents and waves at the sediment/water interface. These sediments have a critical shear stress less than 1 dyne/cm$^2$ and are easily resuspended. Higher values of $\tau_{cr}$ between 2 and 10 dyne/cm$^2$ for sediment buried more than a few inches are typical for well consolidated ocean sediments. Table 1 shows values of $\tau_{cr}$ used for all PDS simulations. The value of $\tau_{cr}$ chosen for the first two layers of sediment resulted in noticeable resuspension under 2-3 m waves for the events during the period February-May 1996. These results are in agreement with the SAIC turbidity data. Some resuspension was calculated for lesser wave events, but the resulting concentrations were negligible. The parameter values for the lower layers shown in Table 1 are reasonable estimates for fairly well consolidated cohesive sediments below the surficial layer. To determine values more accurately for the PDS site would require extensive testing of the proposed cap sediments to determine resuspension potential. Without such data, the above mentioned values represent a reasonable first estimate for the change in sediment characteristics within the upper one to two feet of sediment and fall within the expected experimental range (Lavelle, 1984).

As previously mentioned, the values of $A_0$ and $\tau_{cr}$ for the first two layers presented in Table 1 were chosen based on a comparison of the SAIC data derived suspended solids values for April 6-18 to LTFATE model output for the same period. Various values of the parameters within the experimental range were tested and those that seemed to compare reasonably well to the field data were selected. The results of the simulations for the April 6-18 period indicated that using either current inputs, SAIC current meter data or ADCIRC simulation results, produced similar magnitudes of erosion. The total erosion for the two simulations differed less than 8%. This is because the dominant force in the sediment resuspension is the wave generated stresses. The current velocities from the two sources were similar in magnitude but varied significantly in direction. Therefore the direction in which the sediment plume traveled and thus the TSS concentrations at a specific location varied between the two simulations. Both simulations resulted in peak vertically averaged suspended solids concentrations for the first of three events in the calibration period (maximum wave height of 3.45 m) of approximately 4 mg/l at the site of the SAIC measurement tripod. This is significantly less than the approximately 65 mg/l (maximum) measured by the near bottom turbidity instrument, but, as previously stated, a direct comparison is not possible because the field data are near bottom. Vertically averaged concentrations (model output) will be significantly lower than near bottom concentrations and an order of magnitude reduction was considered an acceptable match for these simulations. Therefore 4 mg/l concentrations vertically averaged over the entire water column may indicate close to 65 mg/l near bottom concentration. Similarly, LTFATE model simulations predict maximum TSS concentrations of approximately 1 mg/l at the tripod during the second event on April 10, compared to 8 mg/l maximum from the field data. Maximum vertically averaged concentrations for any location during the simulation were approximately 25 mg/l near the center of the LTFATE PDS configuration.

LTFATE simulations indicate an order of magnitude less maximum TSS concentrations at the tripod during the third storm (maximum wave height of 5.38 m) in the April 6-18 calibration period when compared to the first event. The SAIC data indicate maximum concentrations of approximately 45 mg/l, compared to only 0.3 mg/l for

LTFATE. The probable reason for the significantly lower LTFATE predicted concentrations compared to the SAIC data is due to the measurement by the turbidity meter of sediments transported to the site from other locations that are not simulated by LTFATE. The suspended solids boundary concentrations for the LTFATE simulations were assumed to be zero. In reality some sediment would be advected from other sites near the PDS and would settle at the PDS after the first two events occurred (creating a new surficial layer for the third event). Because no data were available and because the rocky outcrops may block some sediments from reaching the PDS (depending on the flow direction), all boundary concentrations at inflow locations for the model were assumed zero. Therefore, once the resuspended plume left the PDS, no new sediment was available for deposition. When the second event occurred, there was no surficial layer at the LTFATE PDS and erosion rates for the now exposed lower layers of sediment were considerably less. This resulted in artificially low LTFATE predicted TSS concentrations from the second event. It is interesting to note that despite the larger wave height (and thus higher bottom stresses) during the second event in the calibration period, that the turbidity data indicate lower TSS concentrations than during the first event. This is also the case for TSS concentrations during the third and largest event (storm 7) when compared to the first event (storm 5). This would indicate that despite re-deposition, the surficial layer has not yet fully redeveloped from the first event.

The maximum calculated erosion depth at any location on the PDS for the April 6-18 calibration period was 1.1 cm and the total volume of sediment eroded from the site was 850 $m^3$. Figure 5 is a contour plot of the erosion from the calibration period. The values of $\tau_{cr}$, $A_0$, and $m$ were estimated from the above calibrations and are reasonable first estimates. As previously stated, the lower layers of sediment were given characteristics comparable to other well consolidated ocean sediments. When applied to other events during the SAIC data collection period, the LTFATE simulations using the inputs described above produced reasonable results. These simulations indicated erosion during the events where the field data indicated increased turbidity, although the wave height and thus the erosion amounts were considerably less than the events during the April 1996 calibration period.

## 2.3 Results for Storm Calculations

LTFATE has the ability to simulate either long (year) or short (several days) periods of time. The long term simulations are used when significant erosion occurs frequently. As the SAIC data suggest, normal non-storm conditions do not produce erosion at the PDS (i.e., turbidity levels converted to TSS suggest near zero concentrations and therefore do not support significant erosion). Even events such as the April, 1996 storms resulted in minimal computed erosion with most locations experiencing less than 1 cm loss, and some of this loss would have been diminished by additional deposition had outside sediment advected to the site. Therefore, to determine site erosion potential, only the largest events (and not entire years) need be considered. To this end, the WIS hindcast data for the Atlantic coast (Brooks and Brandon, 1995; Tracy and Cialone, 1996) were analyzed and the five largest storms based on significant wave height for the period simulated (1976-1994) were chosen to determine the erosion potential from the PDS. The station selected to reflect the deep water wave height used as LTFATE input was WIS station 100. This station is located in 100 m of water at 43.50 degrees north latitude and 69.75 degrees west longitude, approximately 42 km directly east of the PDS (Figure 1b) and is exposed to the same fetch as the PDS. The model shoals the deep water waves to reflect what the wave heights would be at the PDS, although at this site (with 40-70 m water depths) shoaling does not significantly reduce deep water wave heights. These shoaled wave values, which vary within the PDS depending on water depth at each location (cell), are then used in the simulations to determine bottom orbital velocities. The five storms chosen for simulation are detailed in Table 2. The maximum deep water wave height for any storm was 14.8 m (reduced by shoaling less than 15%). An event with this magnitude of wave height will clearly have a significant impact on the sediment bed at 60 m. The current conditions and tidal elevations necessary for LTFATE inputs for each of these storms were developed using the ADCIRC circulation model described previously in the text. Each event was simulated with time varying wave and hydrodynamic forcings described above.

Table 2 includes a summary of the findings for the LTFATE modeling of the storms. January and February 1978 storms were combined into one 34 day period (with two peaks in the wave height) because the events were so close that they can reasonably be modeled as one large event (i.e., sediment layers were not reset between the two events). These two storms had the largest estimated wave heights for the entire WIS hindcast, measuring 14.8 m and 12.1 m respectively for each of the storms. As can be seen, the maximum depth of erosion from any of these events is approximately 0.11 m during the 1978 storms. This is a significant amount of erosion, but reasonable considering the magnitude of storm. The total volume of erosion from this storm was $1.4 \times 10^5$ $m^3$. The other events, with maximum wave heights less than 11 m resulted in 0.05-0.08 m maximum depth of erosion and between $6.9 \times 10^4$ and $9.6 \times 10^4$ $m^3$ of erosion from the site. Figure 6a is a contour plot of erosion depths at the LTFATE PDS for the 1978 storms and Figure 6b is the results for the more modest 1979 storm. It should be stated that this is, for the most part, the gross erosion. The net erosion would likely be less because of the influx and re-deposition of sediments eroded from areas outside the PDS. The assumed zero TSS concentration at inflow boundaries does not permit as thick a new layer of sediment to replenish the eroded bed compared to the case where a non-zero TSS concentration is specified. The model does, however, simulate redeposition of sediments eroded at the PDS. This does have an impact on the total volume of erosion. For example, total erosion for the January 1979 event would be approximately 20% greater if no re-deposition of locally eroded sediments occurred.

The values of *Ao* presented for the lower layers of sediment in Table 1 are reasonable for well consolidated open ocean sediments, but there is a possibility that the PDS sediments, especially those recently placed as part of maintenance dredging, are more easily eroded than, for example, San Francisco Bay sediments from which the value of *Ao* for the lowest layer was derived (Parthenaides, 1965). To reflect this possibility, the storms were simulated again assuming the value of *Ao* for each layer except the top two (which were calibrated with the TSS data) was five times the value presented in Table 1 (four times the value for layer 3) and the bottom layer was combined with the seventh layer above it. The values for *Ao* for these simulations are presented in Table 3. As would be expected, the erosion amounts were significantly higher. The predicted erosion amounts, however, were not five times as great due to the layers reflecting increased resistance to erosion. The results of these simulations are presented in Table 4. The maximum erosion for any storm using the Table 3 parameters is 0.22 m during the 1978 34 day event (Figure 7). The other storms of record experienced approximately 0.09-0.1 m maximum erosion. The total volume of erosion predicted for the 1978 event is $2.6 \times 10^5$ $m^3$ and half or less of this amount for the other storms. Again, these erosion depths and volumes would be reduced if off-site sediment were advected to the PDS.

# 3.0 CONCLUSIONS

Despite the deep water at the PDS, moderate erosion due to wave action is possible and should be factored into cap design. Modest events, such as the ones experienced at the site during the 1996 data collection period apparently pose little threat to mound stability. Model predictions of approximately 1 cm maximum erosion depth would be less with redeposition of sediment advected to the site from other locations. Greater erosion is confined to the few episodic events with return periods of several years. WIS hindcasts indicate that the region is susceptible to very large waves. Orbital velocities produced by these waves result in substantial shear stress at the PDS. It would appear that the erosion even from deep water waves on the order of 14.8 m would not penetrate more than 0.22 m using conservative values for the erosion parameters, and only 0.11 m using the bottom layer parameter values determined for San Francisco Bay sediments. These erosion depths would be even lower if re-deposition of sediments transported from other sites were included in the simulations.

As previously stated, the values of $A_0$ can vary over orders of magnitude, but the higher values are reserved for freshwater lakes and rivers and values deemed reasonable for open ocean sediments were used for this modeling project. There is still considerable room for variability in the value of $A_0$ and this variation would significantly alter the model erosion estimates. An order of magnitude less erosion than the model predictions is a possibility. The possibility of an order of magnitude more erosion, however, would be almost impossible. This rate of erosion would create enormous near bottom sediment concentrations and, as previously mentioned, the near bottom currents at the PDS are small. Therefore, although there is sufficient energy to suspend large amounts of sediment, there is little current to transport it off site. At these concentrations the majority of sediment (especially the coarse grained fraction) would quickly settle back onto the bed thus reducing the net erosion significantly.

These initial calculations indicate that, except for the surficial sediments (top 0.2 m), disposal mounds are safe from erosion during high intensity, low frequency events. A moderately (0.6-1.0 m) thick cap with fairly strong resistance to erosion (sediment characteristics similar to the erosion parameters simulated in this modeling effort) could completely isolate the placed material during rare strong storms. However, initially it would be necessary to examine the cap after large wave events (for example, events with wave magnitude comparable to the January 1978 event) to assess cap damage by determining thicknesses of erosion and to establish if cap replenishment is necessary.

## 3.1 Recommendations for Future Studies

It should be reiterated here that results derived from this modeling effort should only be used as a guideline for quantifying erosion potential. The erosion amounts can only be considered approximate without further validation from field data. Assumptions made concerning sediment and site characteristics result in significant model uncertainty. A field data collection effort to determine variation in erosion potential with depth of PDS sediments under high stress conditions would significantly reduce this uncertainty. In addition, further analysis to determine variation in bottom roughness, variation in the suspended solids plume with height above the water column, boundary condition concentrations, data concerning bottom bathymetry changes during storm periods, data from a large return period (significant wave height approximately 6 m) event, and locations of rocky outcrops verses sediment deposits would further refine the model and reduce uncertainty. Another possibility, if the data were available to support such a model, would be to use a three-dimensional model to more accurately reflect the complex bottom hydrodynamics and sediment transport that are inherent in a complex bottom bathymetry like the PDS. This would require an order of magnitude more detailed modeling effort than the LTFATE screening level model.

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| Layer | Depth below sediment/water interface (cm) | $A_0$ ($g/cm^2/s$) | $\tau_{cr}$ ($dynes/cm^2$) |
|---|---|---|---|
| 1 | 0.0-0.75 | $3.9x10^{-6}$ | 0.24 |
| 2 | 0.75-1.50 | $2.0x10^{-6}$ | 0.48 |
| 3 | 1.50-3.0 | $4.9x10^{-7}$ | 2.40 |
| 4 | 3.0-4.5 | $4.9x10^{-8}$ | 4.80 |
| 5 | 4.5-6.1 | $3.7x10^{-8}$ | 9.60 |
| 6 | 6.1-9.1 | $2.5x10^{-8}$ | 9.60 |
| 7 | 9.1-12.2 | $9.8x10^{-9}$ | 9.60 |
| 8 | >12.2 | $2.0x10^{-9}$ | 9.60 |

Table 1: Parameter values for equation 21 - cohesive sediment erosion rates.

| Event Date | Deep Water Maximum Wave Height (m) | Wave Period at Maximum Wave Height (s) | Maximum Depth of Erosion (m) | Total Volume of Erosion ($m^3$) |
|---|---|---|---|---|
| 2/23-27/77 | 10.8 | 13 | 0.05 | $6.9 \times 10^4$ |
| 1/7/78-2/9/78 | 14.8 | 15 | 0.11 | $1.4 \times 10^5$ |
| 1/20-27/79 | 10.9 | 13 | 0.06 | $7.8 \times 10^4$ |
| 3/20-24/80 | 10.2 | 13 | 0.06 | $7.5 \times 10^4$ |
| 3/27-31/84 | 10.2 | 13 | 0.08 | $9.6 \times 10^4$ |

Table 2: Erosion during five largest storm events, 1976-1994.

| Layer | Depth below sediment/water interface (cm) | $A_0$ ($g/cm^2/s$) | $\tau_{cr}$ ($dynes/cm^2$) |
|---|---|---|---|
| 1 | 0.0-0.75 | $3.9x10^{-6}$ | 0.24 |
| 2 | 0.75-1.50 | $2.0x10^{-6}$ | 0.48 |
| 3 | 1.50-3.0 | $2.0x10^{-6}$ | 2.40 |
| 4 | 3.0-4.5 | $2.0x10^{-7}$ | 4.80 |
| 5 | 4.5-6.1 | $1.5x10^{-7}$ | 9.60 |
| 6 | 6.1-9.1 | $1.0x10^{-7}$ | 9.60 |
| 7 | 9.1-12.2 | $3.9x10^{-8}$ | 9.60 |

Table 3: Parameter values, to reflect increased erosion potential, for equation 21 - cohesive sediment erosion rates

| Event Date | Deep Water Maximum Wave Height (m) | Wave Period at Maximum Wave Height (s) | Maximum Depth of Erosion (m) | Total Volume of Erosion ($m^3$) |
|---|---|---|---|---|
| 2/23-27/77 | 10.8 | 13 | 0.09 | $1.1 \times 10^5$ |
| 1/7/78-2/9/78 | 14.8 | 15 | 0.22 | $2.6 \times 10^5$ |
| 1/20-27/79 | 10.9 | 13 | 0.10 | $1.1 \times 10^5$ |
| 3/20-24/80 | 10.2 | 13 | 0.09 | $1.1 \times 10^5$ |
| 3/27-31/84 | 10.2 | 13 | 0.10 | $1.3 \times 10^5$ |

Table 4: Erosion during five largest storm events, 1976-1994, with increased values of $A_0$.

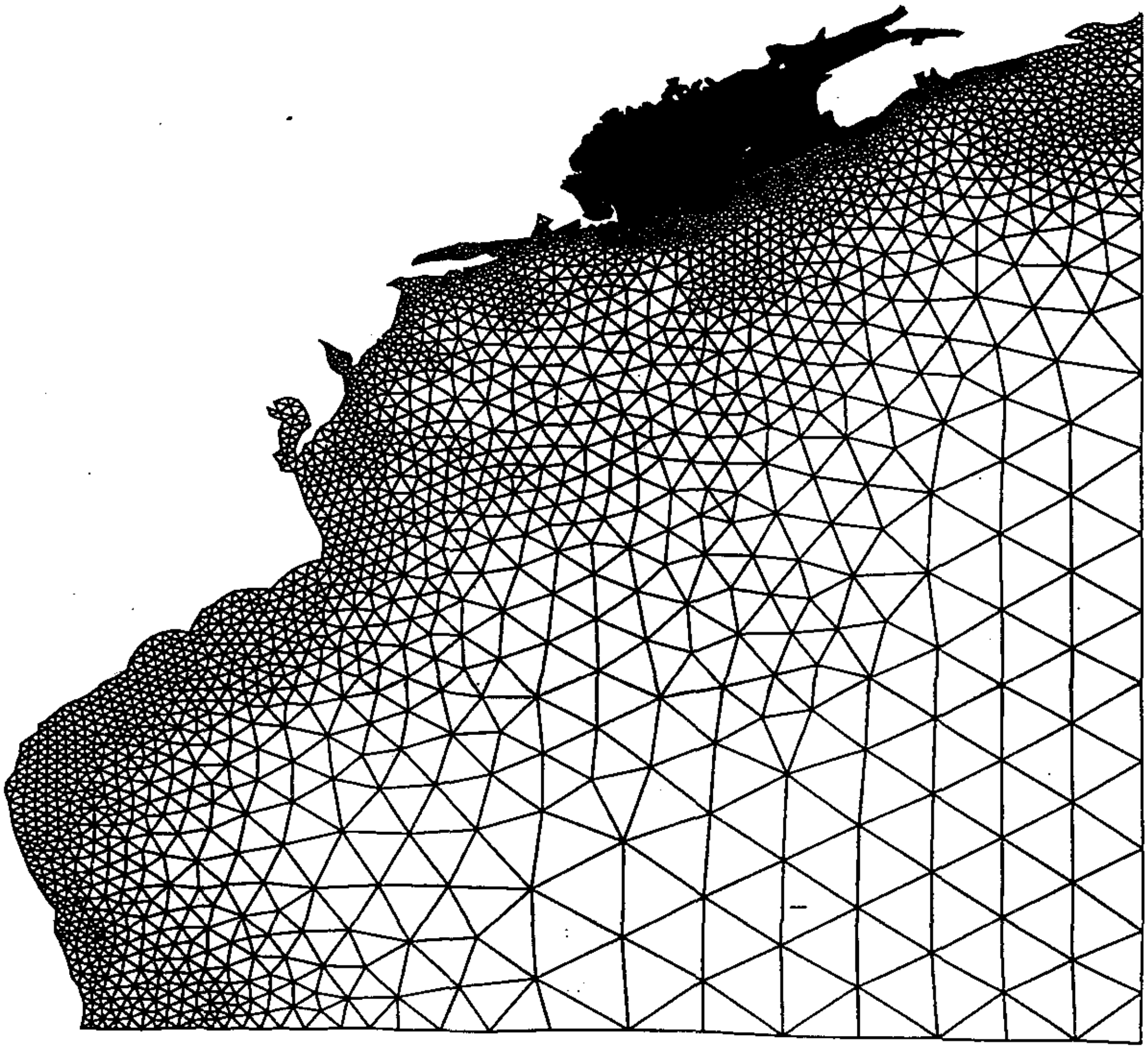

Figure 1a: Adcirc Grid for East Coast

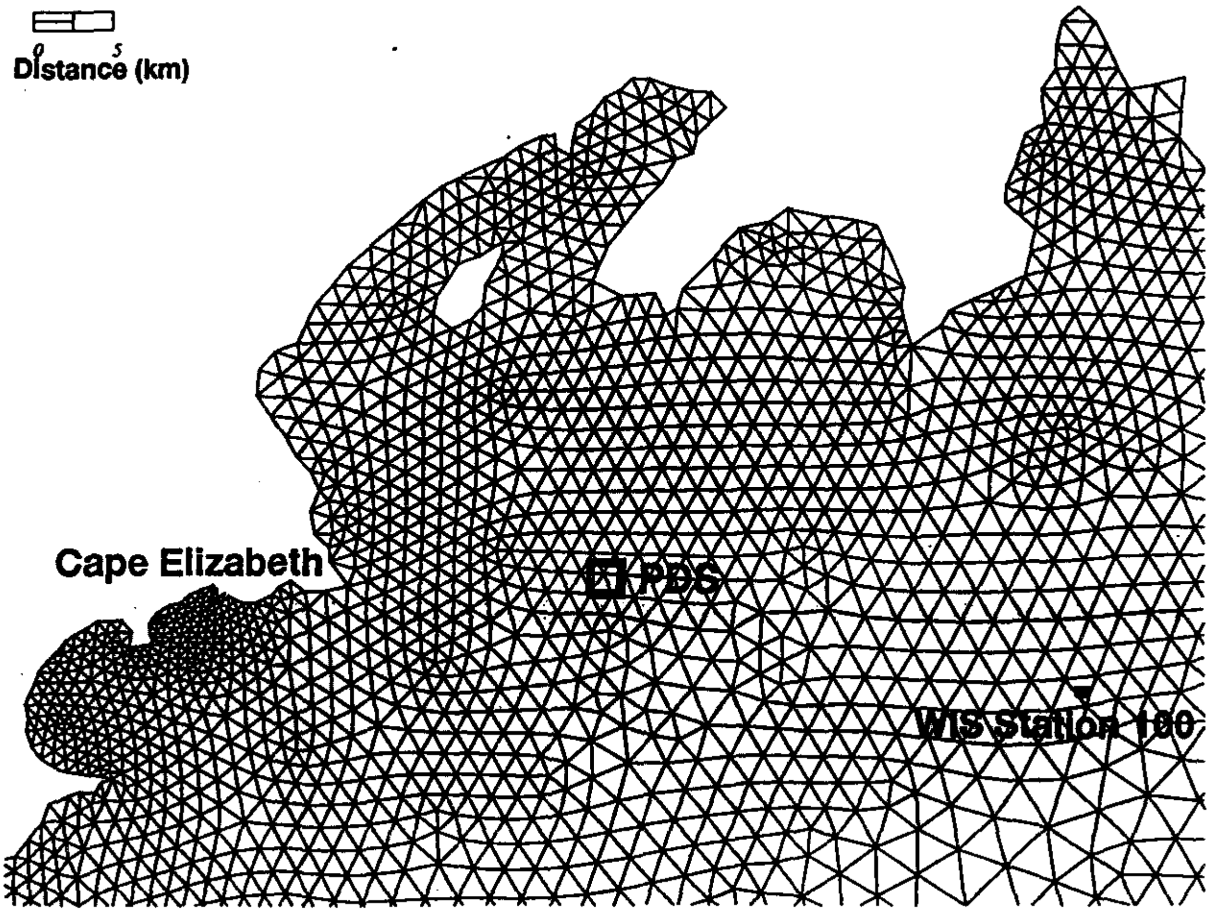


Figure 1b: ADCIRC grid near Portland Disposal Site

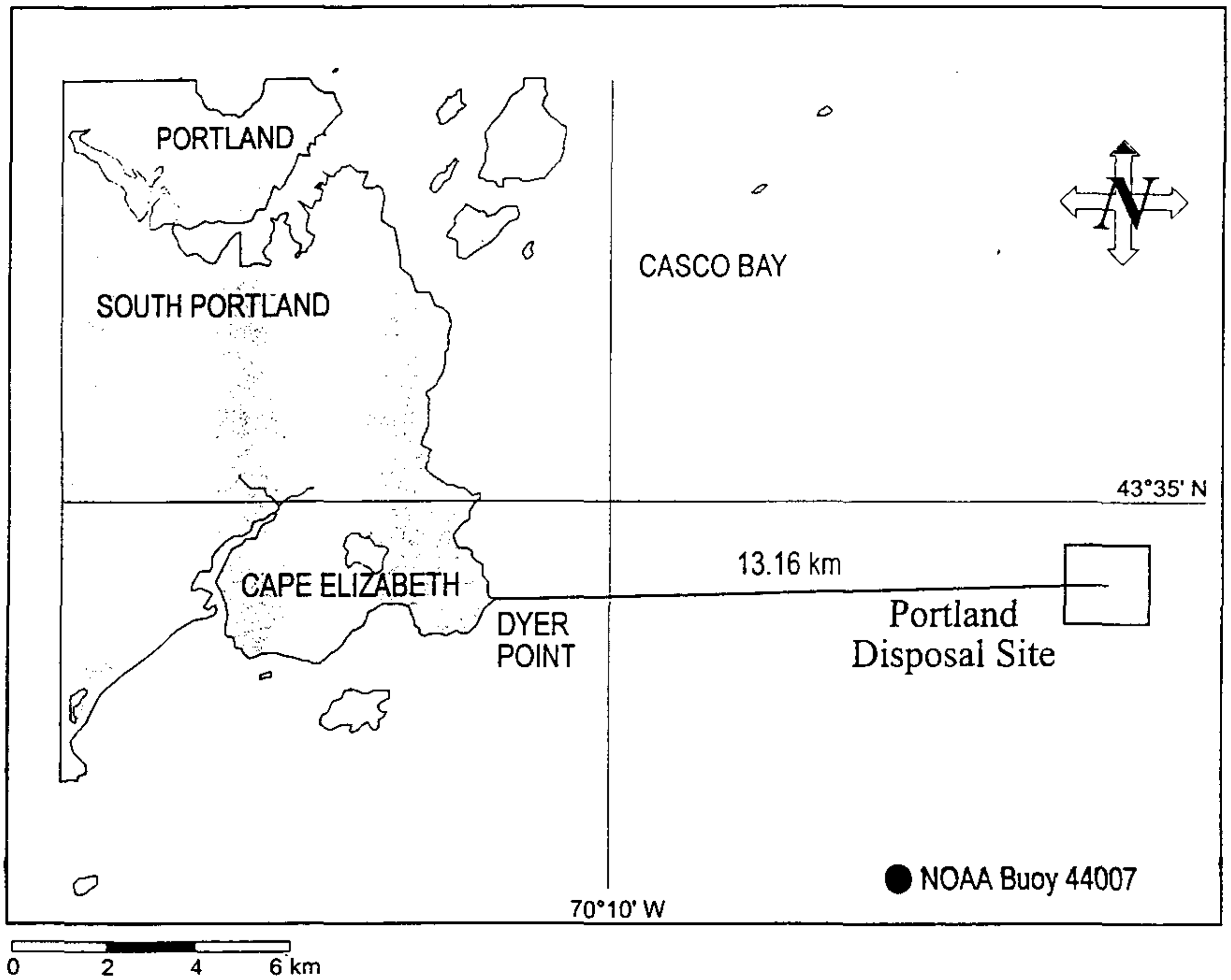


Figure 2: Location of Portland Disposal Site (PDS) from McDowell and Pace (1996)

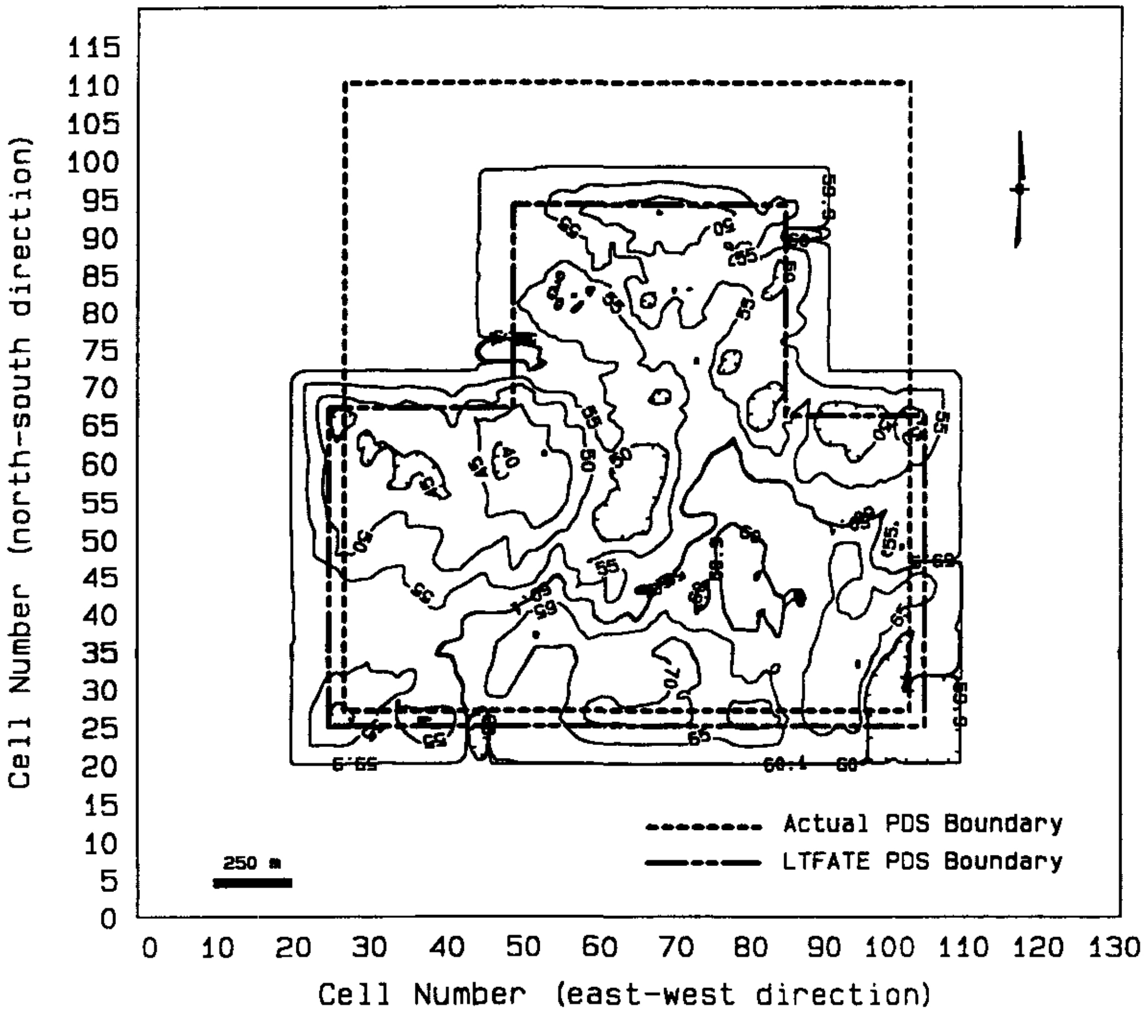


Figure 3a: LTFATE PDS bathymetry (meters below the water surface relative to MLLW). Note: each cell is equivalent to 25x25 m.

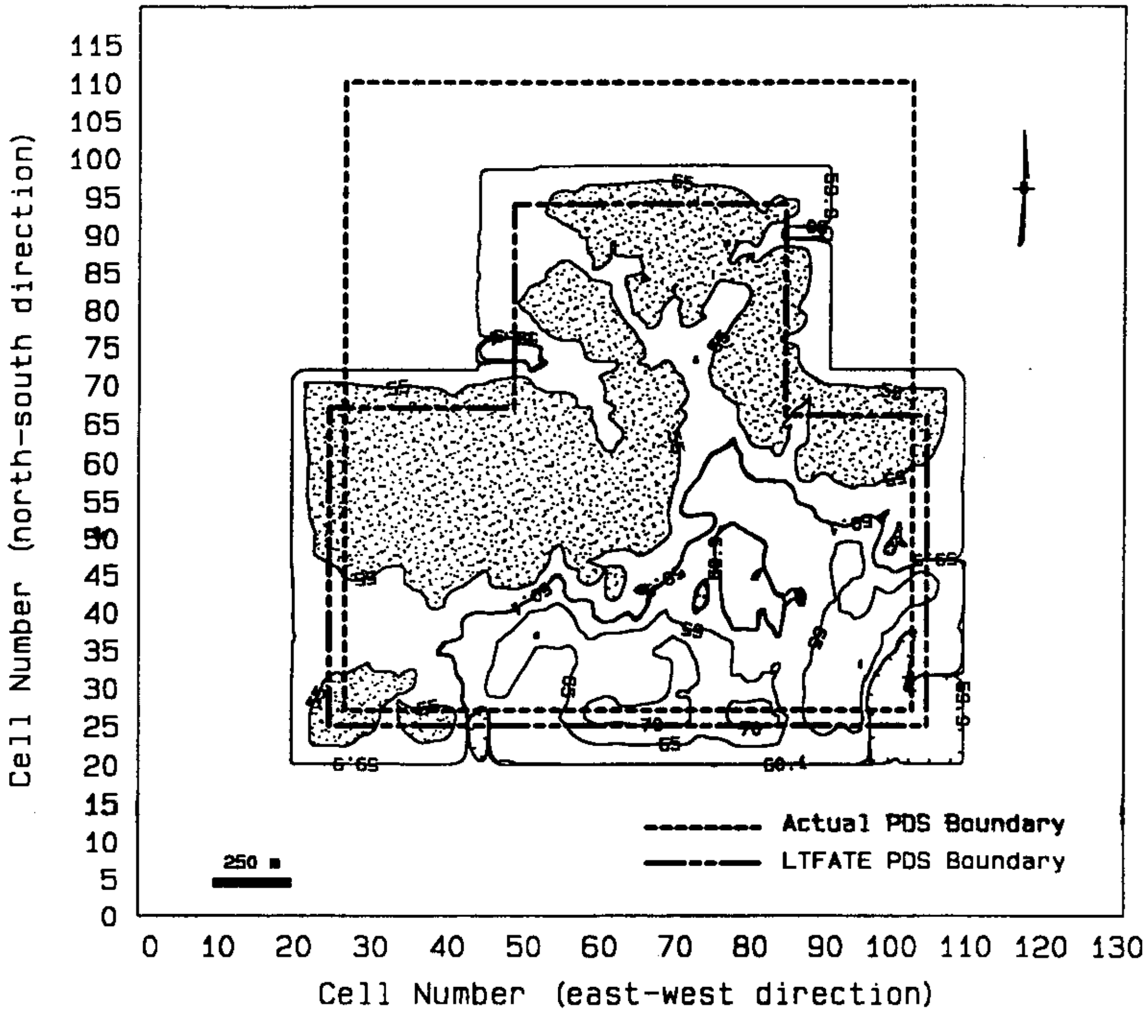


Figure 3b: LTFATE PDS bathymetry (meters below the water surface relative to MLLW), with areas shallower than 55 m stippled. Note: each cell is equivalent to 25x25m.

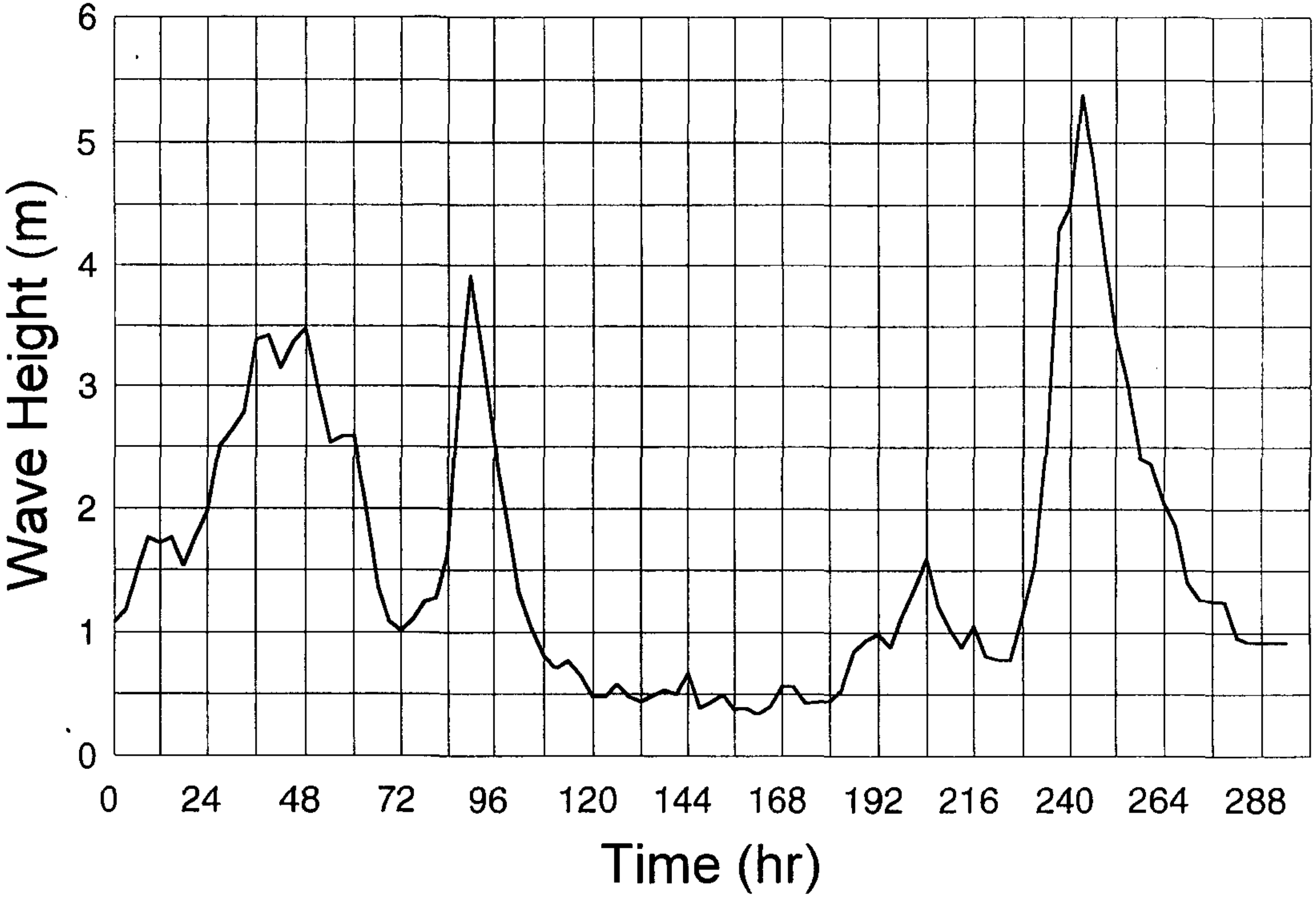


Figure 4: Wave heights (m) during calibration period, April 6-18, 1996.

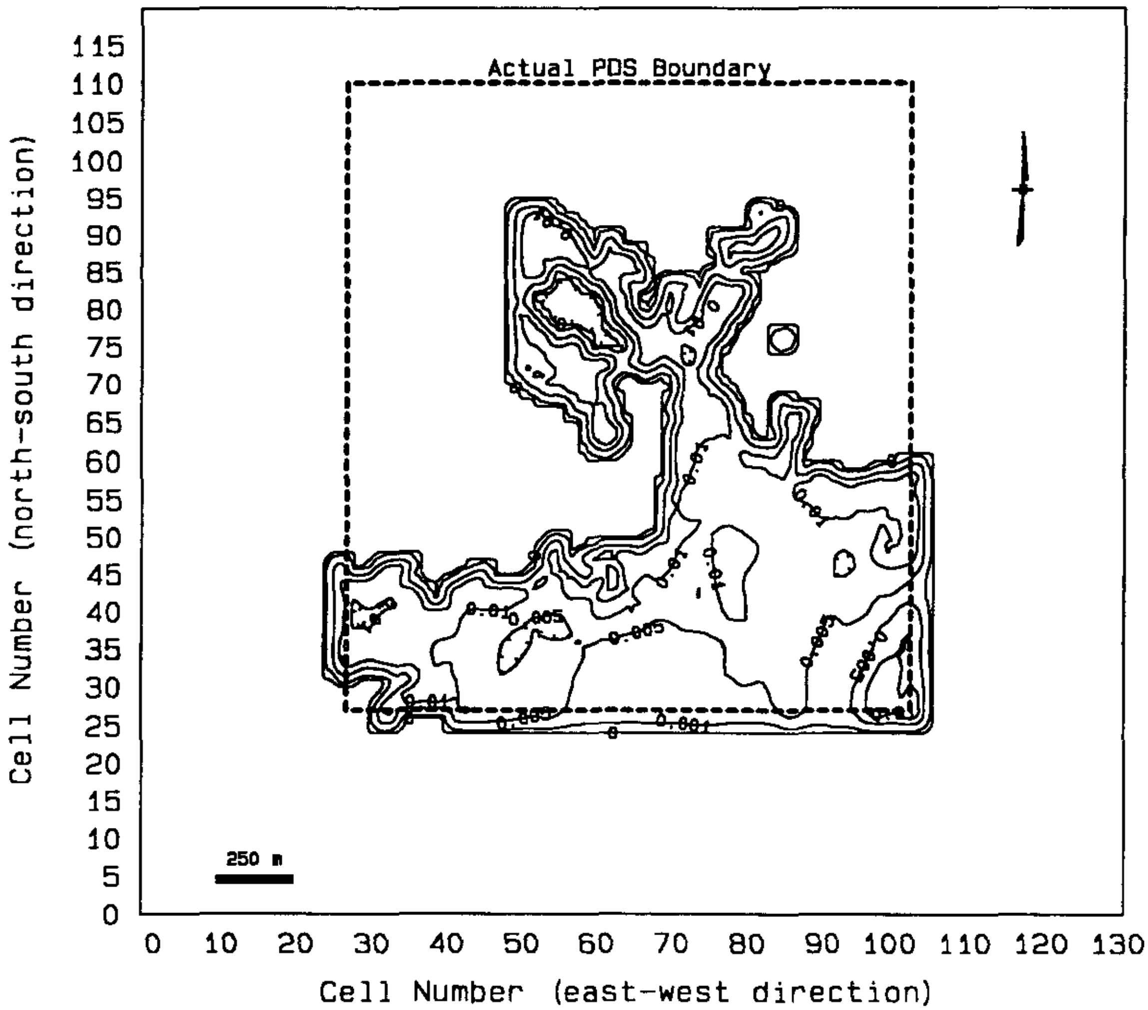


Figure 5: Erosion for calibration period, April 9-18, 1997. Contours shown are 0, 0.001, 0.005, and 0.01. Note: each cell is equivalent to 25 m.

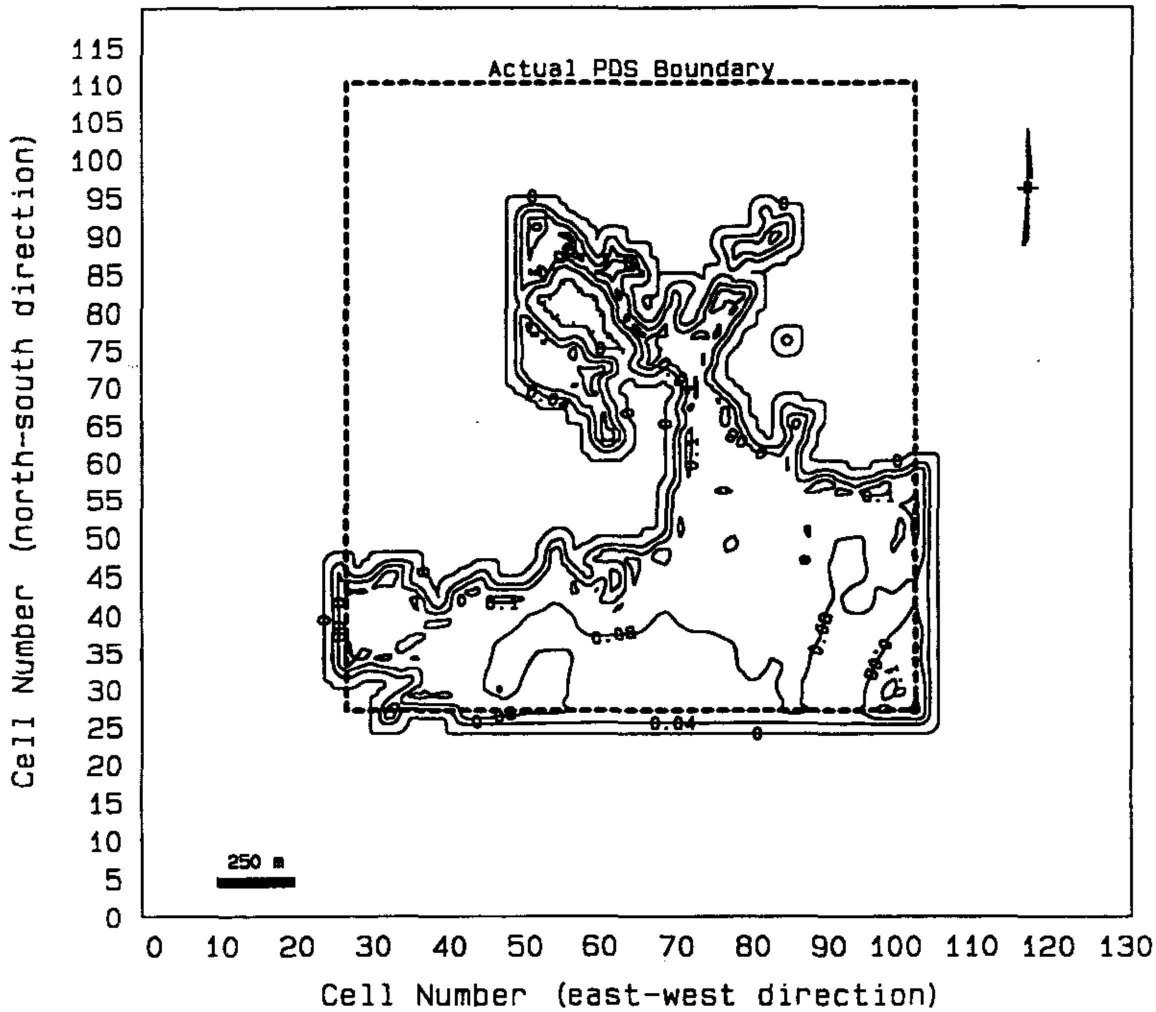


Figure 6a: Erosion for largest event in WIS hindcast, January - February 1978. Contours shown are 0, 0.04, 0.08, and 0.1 m.

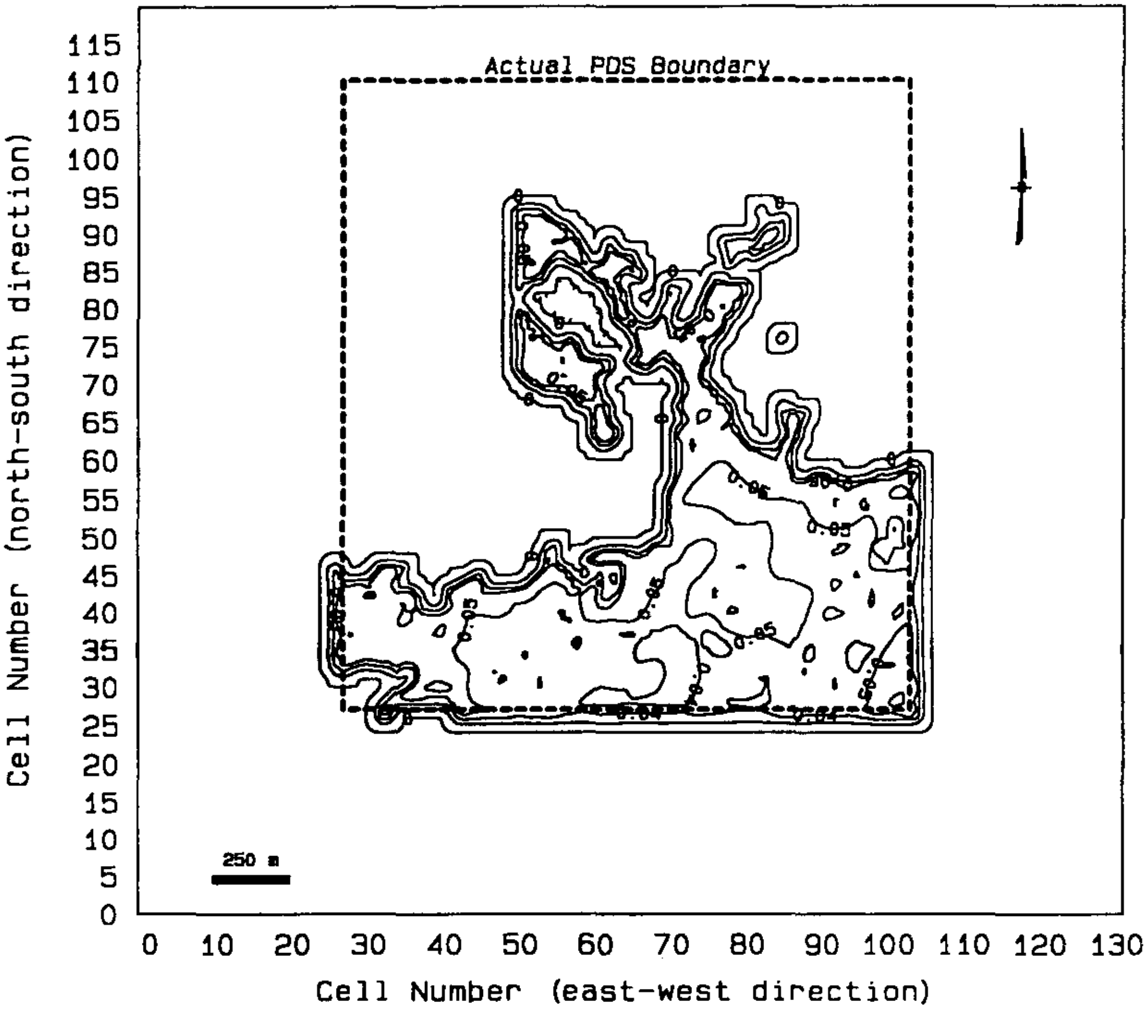


Figure 6b: Erosion for January 1979 event. Contours shown are 0, 0.02, 0.04, and 0.05 m.

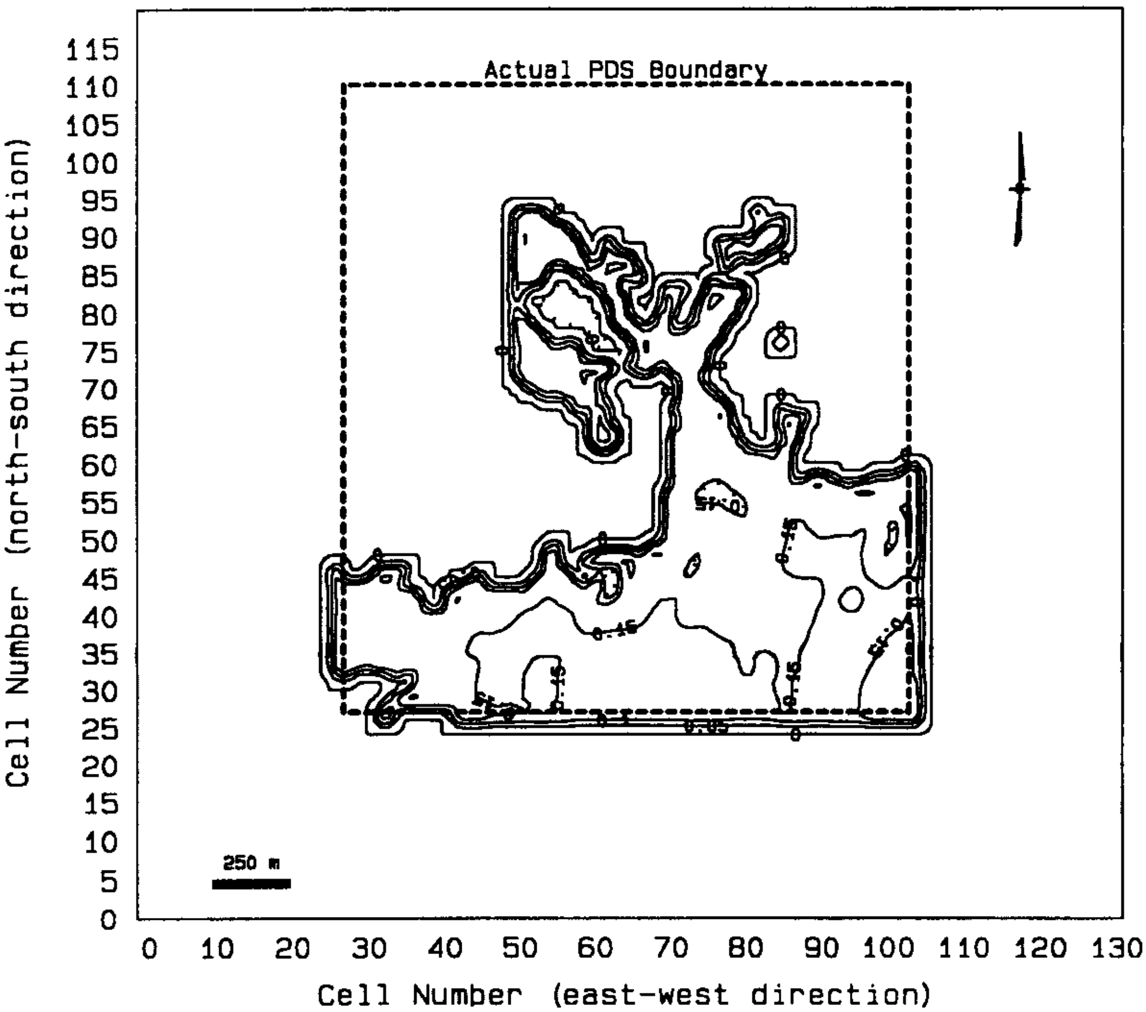


Figure 7: Erosion for largest event in WIS hindcast, January - February 1978, using conservative erosion parameters in Table 3. Contours shown are 0, 0.05, 0.10, 0.15, and 0.20 m.