PNNL-15477

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Preliminary Assessment of Potential Impacts to Dungeness Crabs from Disposal of Dredged Materials from the Columbia River

W.H. Pearson
M.C. Miller
G. D. Williams
N. P. Kohn
J. R. Skalski

February 2006

Prepared for
the U.S. Army Corps of Engineers, Portland District
Portland, Oregon
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

This document was printed on recycled paper.

(9/2003)

PNNL-15477

Preliminary Assessment of Potential Impacts to Dungeness Crabs from Disposal of Dredged Materials from the Columbia River

W.H. Pearson
M.C. Miller
G. D. Williams
N. P. Kohn
J. R. Skalski[1]

Marine Sciences Laboratory
Sequim, Washington

February 2006

Final Report

Prepared for
the U.S. Army Corps of Engineers, Portland District
Portland, Oregon
under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

[1] University of Washington
Seattle, Washington

ABSTRACT

Dredging of the Columbia River navigation channel has raised concerns about dredging-related impacts on Dungeness crabs (*Cancer magister*). The overall objectives of this effort are to synthesize what is known about disposal effects on Dungeness crabs (Phase 1) and to offer approaches to quantify the effects, including approaches to gain a population-level perspective on any effects found in subsequent studies (Phase 2). This report documents Phase 1, which included 1) development of a conceptual model to integrate knowledge about crab biology and the physical processes occurring during disposal, 2) application of physics-based numerical modeling of the disposal event to understand the physical forces and processes to which a crab might be exposed during disposal, 3) conduct of a vulnerability analysis to identify the potential mechanisms by which crabs may be injured, and 4) recommendations of topics and approaches for future studies to assess the potential population-level effects of disposal on Dungeness crabs. The conceptual model first recognizes that disposal of dredged materials is a physically dynamic process with three aspects: 1) convective descent and bottom encounter, 2) dynamic collapse and spreading, and 3) mounding. Numerical modeling was used to assess the magnitude of the potentially relevant forces and extent of mounding in single disposal events. The modeling outcomes show that predicted impact pressure, shear stress, and mound depth are greatly reduced by discharge in deep water and somewhat reduced at longer discharge duration. The analysis of numerical modeling results and vulnerabilities indicate that the vulnerability of crabs to compression forces under any of the disposal scenarios is low. Modeling results and other information suggest that crabs may be vulnerable to injury from surge currents under some but not all disposal scenarios. For the shallow-water, short-duration disposal scenarios, the shear stress and surge currents estimated from the modeling and observed in the field at Palos Verdes appear to be sufficiently high to mobilize and transport bottom sediment and at least juvenile crabs. The surge currents estimated from modeling the deep water scenarios are not sufficient to mobilize sediment greater than 1 mm or juvenile crabs. The effects of such movement, if any, are not known and can be reduced by behavioral responses by crabs. There is evidence that burial by dredged materials can affect crab respiration and survival, but confounding factors in previous experiments preclude conclusions about thresholds and extent of effects. We recommend that future studies focus on burial effects during shallow water, short duration disposal scenarios and take into account the potential for behavioral responses to mitigate any effects.

Executive Summary

Dredging of the Columbia River navigation channel has raised concerns about dredging-related impacts on Dungeness crabs (*Cancer magister*). The Portland District, U.S. Army Corps of Engineers (Corps) engaged the Marine Sciences Laboratory (MSL) of the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) to review the state of knowledge concerning impacts on Dungeness crabs resulting from disposal during the Columbia River Channel Improvement Project and also during annual maintenance dredging in the Mouth of the Columbia River (MCR). MSL designed a phased examination of the potential effects of disposal on Dungeness crabs during dredging of the Columbia River. The objectives of the overall effort are to synthesize what is known about disposal effects on Dungeness crabs (Phase 1) and offer approaches to quantify the effects, including approaches to gain a population-level perspective on any effects (Phase 2). This report documents Phase 1 of the effort, which included the following steps:

- Develop a conceptual model to integrate knowledge about crab biology and the physical processes occurring during disposal
- Apply physics-based numerical modeling of the disposal event to understand the physical forces and processes to which a crab might be exposed during disposal
- Conduct a vulnerability analysis to identify the potential mechanisms by which crabs may be injured
- Recommend topics and approaches for future studies to assess the potential population-level effects of disposal on Dungeness crab.

The conceptual model first recognizes that disposal of dredged materials is a physically dynamic process with three aspects, each of which could affect Dungeness crab:

- *Convective Descent and Bottom Encounter.* At bottom encounter, the conversion of the momentum attained during the fall (convective descent) of dredged materials produces compression and shear forces on the bottom.
- *Dynamic Collapse and Spreading.* During dynamic collapse, the vertical momentum of the falling materials is converted to the horizontal, and the dredged materials spread along the bottom away from the area of bottom encounter. The shear forces produce surge currents along the bottom that may mobilize bottom sediment.
- *Mounding*. As falling and spreading materials come to rest, the materials form a disposal mound, which may bury crab. This process is also influenced by passive transport-dispersion during which the material transport and spreading may be determined more by ambient currents and turbulence than by the dynamics of the disposal operation.

During disposal, the characteristics of the dredged materials (e.g., size distribution, cohesiveness), the water column (e.g., depth, stratification, currents), and the bottom (e.g., slope, grain-size distribution) interact to determine the characteristics of the disposal plume, impact of falling materials on the bottom, the horizontal spread of materials, and the resulting disposal mound.

The preliminary assessment with the conceptual model suggested that the nature and potential extent to which compression, shear forces, and burial depth could injure crabs needed to be determined. Therefore, the next major task in Phase 1 was to conduct numerical modeling of the disposal process to assess the magnitude of the potentially relevant forces and extent of mounding in single disposal events. The Short-term Fate (STFATE) dredged material disposal model developed by the US Army Corps of Engineers, Engineer Research and Development Center in Vicksburg, Mississippi, was used to estimate impact force, shear force, and mound thickness during a disposal event. A matrix of disposal conditions was developed for the two dredges most likely to be used in the Lower Columbia River dredging operations, the *Essayons* and the *Sugar Island*. The water depths selected for modeling represent conditions at the North Jetty disposal site (45 ft) at the MCR, the shallow-water ocean dredged materials disposal site (65 ft), and the shallower and deeper ends of the deepwater disposal site (230 ft and 280 ft). Current velocity conditions at the sites were considered uniform from surface to bottom for all cases, and were taken as 2 ft/s for 45-ft and 65-ft depths, and 1 ft/s for 230-ft and 280-ft depths. The current direction was applied in the direction of vessel motion for all cases. The model was run for each vessel moving parallel to the isobaths, perpendicular to the isobaths, and over a flat bottom. A constant bottom slope of 1:100 was selected for the 45-ft and 65-ft water depths and 1:200 for 230-ft and 280-ft cases. A total of 36 test scenarios were used in the STFATE numerical model to estimate 3 parameters thought to affect *C. magister*: 1) vertical impact pressure developed by the convective descent, 2) the horizontal shear stress generated during dynamic collapse, and 3) the depth of burial following settling of the dredged materials.

The modeling outcomes show that predicted impact pressure, shear stress, and mound depth vary by dredge characteristics and are greatly reduced by discharge in deep water and somewhat reduced at longer discharge duration. The *Essayons* data show that, at the same water depth, greater stresses are developed for the shorter discharge duration. The greatest compression and shear forces are developed by the *Sugar Island*, for which the discharge duration is only 3 min. Even though the *Sugar Island* is disposing less than half the total volume of the *Essayons*, its modeled speed during discharge is more than three times greater (7 knots vs. 2 knots). The comparison of mound thickness among the three discharge duration cases is not as simple, but the greatest mound thickness occurred in shallow (45 ft to 65 ft) water with the dredge discharging parallel to slope or where no slope was assumed.

The analysis of numerical modeling results and vulnerabilities indicate that the vulnerability of crabs to compression forces is low under any of the disposal scenarios. The predicted maximum compression forces are orders of magnitude less than the strength of chitin. Modeling results and other information suggest that crabs may be vulnerable to injury from surge currents under some but not all disposal scenarios. For the deep-water disposal scenarios, the maximum forces and mounding heights are substantially less than those for the shallow water scenarios. The surge currents estimated from modeling the deep water scenarios were not strong enough to mobilize sediment greater than 1 mm or juvenile Dungeness crabs. For the shallow-water, short-duration disposal scenarios, the surge currents estimated from the modeling were comparable to field observations of surge current speeds at Palos Verdes, California from another study. The surge currents from the modeled shallow water disposal and from the Palos Verdes Field observations appear to be sufficiently high to mobilize and transport the bottom sediment and at least juvenile crabs. The effects of such movement by surge current, if any, are not known. Behavioral response to surge currents probably occurs and may reduce the occurrence and extent of movement and any associated impacts. There is evidence that crabs are vulnerable to injury from burial through effects on crab respiration and survival. Loss of the respiratory pathway is a key factor in burial effects. Previous studies indicate that under burial with 10 cm, Dungeness crabs were unable to recover the respiratory pathway and switched to moving up through the sediment, a process that occurred over 24 hours. The observation that crabs can take some hours to emerge after burial suggests that multiple dumps over the same area would increase vulnerability. In most cases, the standard disposal practice is to not dump sequentially at the same location but to systematically spread the dumps over the whole of the disposal site. It is clear that crab behavior reduces vulnerability, but to what extent is much less clear. There are differences in the results of three previous studies at the same burial depth that may be related to tank size and the opportunity for escape behavior. Two questions concerning burial remain. First, if no escape response is permitted, what is the threshold for effects for each age class and molting stage? Second, if escape response is permitted in a realistically designed disposal simulation, to what extent do escape and other behavioral responses reduce exposure to the relevant stressors and the subsequent impacts?

Concerning future studies, we recommend that studies of compression forces be given a low priority. We also recommend that field studies of the disposal process to validate the model results be given a low priority. The disposal scenarios that should be the focus of Phase 2 studies are clearly those for shallow water and short duration. Once threshold values are determined with simulations of the maximum values likely to be attained in realistic disposal scenarios, the potential effects for the other scenarios in deeper water or longer duration can be modeled. The surge currents of interest range from 0.5 m/s to 5 m/s.

The disposal event processes are interlinked. We suggest that because of that interlinking, the questions are best addressed in a mesocosm that can simulate the relevant aspects of the disposal process, specifically the surge currents and mounding. Observation of crab behavior in the turbid conditions that will certainly follow the sediment introduction could be accomplished potentially in two ways: 1) Acoustic tags and 2) the Dual-frequency Identification Sonar (DIDSON) camera. With a mesocosm, experiments can be designed to clearly separate burial effects when no escape response is permitted from those in which escape response is enabled. To gain population-level perspective on any effects determined from the laboratory studies would entail estimates of Adult Equivalent Loss (AEL), which was used previously in estimating crab losses from dredge entrainment. The AEL model that exists now for entrainment losses can be easily modified for the application intended here. The integration of a series of physical and biological models will enable estimation of the population-level impacts of disposal of dredged materials on Dungeness crab.

Contents

Figures

Tables

1.0 Introduction

Dredging of the Columbia River navigation channel has raised concerns about dredging-related impacts on Dungeness crabs (*Cancer magister*) in the estuary, mouth, and nearshore ocean areas of the Columbia River. The Portland District, U.S. Army Corps of Engineers (Corps) engaged the Marine Sciences Laboratory (MSL) of the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) to review the state of knowledge concerning impacts on Dungeness crab resulting from entrainment and disposal during the Columbia River Channel Improvement Project and also during annual maintenance dredging in the Mouth of the Columbia River (MCR). Crab entrainment was directly measured in studies conducted by MSL in 2002 and 2004 (Pearson et al. 2002, 2003, and 2005). Previously, MSL has performed studies for the Corps' Seattle District related to dredging impacts on crabs during the Grays Harbor Navigation Improvement Project (e.g., Pearson 1987, Pearson and Woodruff 1987, Pearson et al. 1987). However, studies were still needed on the potential effects of dredged material disposal on Dungeness crabs specific to the Columbia River.

At the request of the Corps, MSL designed a phased examination of the potential effects of disposal on Dungeness crabs during dredging of the Columbia River. The objectives of the overall effort are to synthesize what is known about disposal effects on Dungeness crabs (Phase 1) and to offer approaches to quantify the effects, including approaches to gain a population-level perspective on any effects (Phase 2). This report documents Phase 1 of the effort, which included the following steps:

- Develop a conceptual model to integrate knowledge about crab biology and the physical processes occurring during disposal
- Apply physics-based numerical modeling of the disposal event to understand the physical forces and processes to which a crab might be exposed during disposal
- Conduct a vulnerability analysis to identify the potential mechanisms by which crabs may be injured
- Recommend topics and approaches for future studies to assess the potential population-level effects of disposal on Dungeness crab.

2.0 Conceptual Model for Potential Effects of Disposal on Dungeness Crabs

The conceptual model first recognizes that disposal of dredged materials is a physically dynamic process (Figure 1) with three aspects, each of which could affect Dungeness crab:

- *Convective Descent and Bottom Encounter*. At bottom encounter, the conversion of the momentum attained during the fall (convective descent) of dredged materials produces compression and shear forces on the bottom.
- *Dynamic Collapse and Spreading*. During dynamic collapse, the vertical momentum of the falling materials is converted to the horizontal, and the dredged materials spread along the bottom away from the area of bottom encounter. The shear forces produce surge currents along the bottom that may mobilize bottom sediment.
- *Mounding*. As falling and spreading materials come to rest, the materials form a disposal mound, which may bury crab. This process is also influenced by passive transport-dispersion during which the material transport and spreading may be determined more by ambient currents and turbulence than by the dynamics of the disposal operation.

During disposal, the characteristics of the dredged materials (e.g., grain-size distribution, cohesiveness), the water column (e.g., depth, stratification, currents), and the bottom (e.g., slope, grain-size distribution) interact to determine the characteristics of the disposal plume, the impact of falling materials on the bottom, the horizontal spread of materials, and the resulting disposal mound. These conditions can vary substantially depending on the disposal scenario.

The literature within the framework of the conceptual model enabled a preliminary assessment of the potential hazards to Dungeness crabs during disposal. For each aspect of disposal, this assessment suggested a different potential mechanism for injury to crabs:

- *Convective Descent and Bottom Encounter*. The nature and potential extent of the compression and shear forces from falling materials has not been considered in the literature. Whether such forces would exist in sufficient magnitude to induce injury during a disposal event needed to be assessed.
- *Dynamic collapse and Spreading*. As the dredged materials spread along the bottom away from the area of bottom encounter, the tumbling of crabs during dynamic collapse could occur and could lead to mechanical injury. The literature indicates that surge currents can occur during disposal. *In-situ* measurements of surge currents of experimental disposal events at Palos Verdes, California demonstrated that for six disposal events, surge currents with speeds between 0.75 m/s and 1.36 m/s occurred at 75 m downslope from the disposal location (Bratos et al. 2002, McDowell et al. 2002). Surge currents at the disposal location would have been higher, but to what extent is unknown.
- *Mounding*. The materials that form a disposal mound may bury crabs. The previous laboratory studies of Chang and Levings (1978), the Corps (USACE 1999), and Antrim and Gruendell (1998) have demonstrated that depth of burial influences survival of Dungeness crab. Antrim and Gruendell (1998) also found that the escape behavior and activity level of the crabs during the disposal event influenced crab survival more than crab size or depth of burial.

Although the physical processes occurring during a disposal event could produce the above three potential mechanisms for injury to Dungeness crabs, the behavior and molting stage of the crabs will also interact with these physical processes to determine the nature and extent of any injuries. In particular, the degree of burrowing and molting stage may influence the effects of the disposal. The conceptual model hypothesizes that these states differ in the types and magnitudes of physical forces that impinge on the crab. At the start of a disposal event, the crab can be in one of several states of burrowing and molting:

- unburrowed, hard shelled
- unburrowed, soft shelled
- partially burrowed, hard shelled
- partially burrowed, soft shelled
- fully burrowed, hard shelled
- fully burrowed, soft shelled.

Although it is not known for certain whether hard-shelled crabs are less vulnerable to compression and shear forces, the presumption has been that soft tissues will tear more easily than hard tissue and, therefore, a crab is more vulnerable to such forces when in a soft-shelled stage. Unburrowed crabs may be less vulnerable to the forces encountered during bottom encounter and less likely to be buried, but may be more vulnerable to tumbling during dynamic collapse. Soft-shelled crabs are presumed to be burrowed or sheltered, so that the unburrowed state for soft-shelled crabs may not be as common as other states. Antrim and Gruendell (1998) found that recently molted, Age 0+ crabs had higher survival (85%) than did Age 1+ and adult crabs (52% and 50%, respectively) and attributed the higher survival to two factors. First, Antrim and Gruendell (1998) reported that the recently molted, Age 0+ crabs were more active and more easily roused from being burrowed than the older crabs. Second, the near-neutral buoyancy of recently molted crabs made them more likely to be lifted into the water column by the surge current produced by the test dump. The angle at which the crab rests relative to the plane of the bottom may vary between the partially and fully burrowed states. The angle during burrowing could influence the shear forces encountered during bottom encounter and dynamic collapse. These observations of Antrim and Gruendell (1998) indicated that the influence of escape responses and activity level on the potential for injury during disposal needs to be taken into account in any assessment of disposal effects.

The overlap in the timing of crab molting and seasonal dredging is such that molting crabs may be exposed to disposal events. Annual dredging of the MCR and disposal in disposal sites at the MCR and near ocean are weather-limited and generally occur from May to September. Most Dungeness crabs megalopae molt into juveniles in April-May off the coasts of Oregon and Washington and may molt six to ten times in the first year (Armstrong et al. 1987, 1991, 2003). The crabs mature at about 2 years and reach marketable size at about 4 years old. Marketable crabs usually molt only once per year. Adult crabs can molt virtually year round, but most molting occurs from April through August or September. Antrim et al. (1994) found that almost all (97%) of the adult crabs at 20- to 40-ft depths in the nearshore areas off Grays Harbor during September were female, and 23% were soft-shelled. Discerning the actual exposure of crabs to disposal events requires the collection and assessment of crab density data specific to the disposal site of concern.

The overlap between disposal events and egg-bearing life history stage appears to be slight. Egg bearing and hatching occurs completely in offshore waters (Armstrong et al. 2003). Egg-bearing female crabs can be found in offshore waters from October through March. Hatching occurs in the ocean in the winter. Disposal operations in the ocean do not occur during fall and winter.

In summary, preliminary assessment using the conceptual model indicated that further assessment was needed concerning potential injury to crabs from compression forces during bottom encounter, from shear forces during dynamic collapse and spreading, and from burial during deposition and mounding. After the preliminary assessment, three questions remained:

1. What are the magnitude, spatial extent, and duration of the relevant forces during disposal?
2. Would the forces during disposal be of sufficient intensity and duration to result in injury to crab?
3. How does crab behavior influence vulnerability to disposal effects?

To address the first two questions, Phase 1 used a physics-based numerical model of the disposal process to better define the magnitude, duration, and extent of the relevant forces and the associated potential for vulnerability and injury.

3.0 Numerical Modeling of Disposal

The preliminary assessment with the conceptual model suggested that the nature and potential extent to which compression, shear forces, and burial depth could injure crabs needed to be determined. Therefore, the next major task in Phase 1 was to conduct numerical modeling of the disposal process to assess the magnitude of the potentially relevant forces and extent of mounding in single disposal events. The Short-term Fate (STFATE) dredged material disposal model developed by the US Army Corps of Engineers, Engineer Research and Development Center in Vicksburg, Mississippi, was used to estimate impact force, shear stress, and mound thickness during a disposal event. An initial modeling effort was conducted with scenarios selected to provide estimates of the relative magnitudes of the forces during the various phases of the disposal process; as such, they were not intended to represent actual disposal scenarios. The next physical-modeling effort was conducted with actual expected disposal scenarios with the specific dredges, dredged materials characteristics, and disposal site characteristics specific to the Columbia River.

3.1 Approach to Numerical Modeling

In Phase 1, initial numerical modeling with the STFATE model was used to investigate the bottom vertical impact forces, the horizontal shear stresses, and the accumulation of disposed material for a variety of dredge operating conditions and water depths. Initial modeled conditions are provided in Table 1. These conditions were not intended to represent actual disposal scenarios, but were chosen to develop estimates of the relative magnitudes of the forces during the various phases of the disposal process. To support further investigation of the potential impacts of dredge disposal on *C. magister*, additional scenarios were run through the STFATE model that more accurately reflect actual Columbia River disposal conditions.

Following a meeting with Portland District Corps engineers, a matrix of disposal conditions was developed for the two dredges most likely to be used in the Lower Columbia River dredging operations, the *Essayons* and the *Sugar Island*. The *Essayons* is a 350-ft, side-arm hopper dredge owned by the Corps (Figure 2). Its normal operating load is 5500 cubic yards (cy) of sediment, which it discharges through bottom doors while moving ahead at about 2 knots. Discharge duration can be controlled by the rate and amount of door opening. Discharge durations of 9 min and 14 min were selected for this study as representative of current disposal practices (Table 2). The Dredge *Sugar Island* (Figure 3) is a trailing suction, hopper dredge owned by the Great Lakes Dredge and Dock Company and operated under contract to the Corps. Its normal operating load is about 2500 cy of material, which it discharges over duration of 3 min while steaming at 7 knots (Table 3).

The water depths selected for modeling represent conditions at the North Jetty disposal site (45 ft) at the MCR, the shallow-water ocean dredged materials disposal site (ODMDS) (65 ft), and the shallower and deeper ends of the deepwater ODMDS (230 ft and 280 ft) (Figure 4). Current velocity conditions at the sites were considered uniform from surface to bottom for all cases, and were taken as 2 ft/s for 45-ft and 65-ft depths, and 1 ft/s for 230-ft and 280-ft depths. The current direction was applied in the direction of vessel motion for all cases. The model was run for the vessel moving parallel to the isobaths, perpendicular to the isobaths, and over a flat bottom. A constant bottom slope of 1:100 was selected for the 45-ft and 65-ft water depths and 1:200 for 230-ft and 280-ft cases. The selected depth, current velocity, and direction relative to bottom slope are summarized for each case in Tables 2 and 3. Using the disposal scenarios described in Tables 2, 3 and 4, test scenarios (n = 36) were used in the STFATE numerical model to estimate the 3 parameters thought to affect *C. magister*: 1) vertical impact pressure developed by the convective descent, 2) the horizontal shear stress generated during dynamic collapse, and 3) the depth of burial following settling of dredged materials from the disposal plume.

3.2 STFATE Outcomes for Expected Disposal Scenarios

The 36 cases representing expected disposal scenarios for the Columbia River were modeled using STFATE. Approximately 20 model runs per scenario were conducted. The modeled output data were sorted to identify the model run with the maximum estimated value for each parameter for each scenario; these results are presented in Table 5. The maximum estimates of impact pressure, shear stress, and mound thickness were observed in the 45-ft water depth and varied somewhat with orientation relative to bathymetric contours. Generally, impact pressure and shear stress maxima were observed when the dredge discharged perpendicular to the isobaths (bottom slope), and mound depth maxima occurred with the no-slope condition. Estimated values for all three parameters declined with depth of the disposal site, as illustrated in Figure 5.

3.2.1 Vertical Impact Pressure

The maximum estimates of vertical impact pressure were observed for the 45-ft water depth disposal site and varied somewhat with orientation relative to bathymetric contours. The maximum predicted vertical impact pressure of 55,669 pascal (Pa) (8.07 pound-force per square inch [psi]) was developed during the 3-min-duration discharge from the *Sugar Island* in 45-ft water depth while the vessel was running perpendicular to the bottom slope (Table 4); these estimates were the same when the vessel was moving parallel to the bottom slope. In contrast, vertical impact pressures for the dredge *Essayons*, although lower than those for the *Sugar Island*, varied widely depending on the bottom slope condition at the 45-ft depth. The *Essayons* vertical impact-pressure estimate for the discharge orientation that was perpendicular to the isobaths (37,611 Pa) was 27% higher than the estimate for the no-slope case (29,580 Pa) (Table 4). These differences are likely due to the *Essayons'* slower vessel speed, longer discharge duration, and larger discharge volume (2 knots, 9 min, 5500 cy).

Vertical impact pressure is expected to build up and decrease relatively gradually, rather than abruptly as, for instance, during a hammer blow. As shown in Figure 6, the peak value of vertical pressure is quite localized, and the magnitude decreases rapidly with distance from the disposal centerline. During shallow-water (45-ft) disposal, impact pressure decreased to zero within 20 m of the disposal centerline for the *Sugar Island* (discharge speed 7 knots, discharge volume 2500 cy) and within 10 m of the disposal centerline for the *Essayons*.

3.2.2 Horizontal Shear Stress

The horizontal shear stress acts along the seabed and is generated as the descending sediment plume changes direction from vertical to horizontal. This stress is similar to the horizontal flow generated by a single wave as it breaks and rushes along a beach, though in the disposal case there is no return flow. As in the case of a wave-generated current, the shear stress has the ability to mobilize and transport unconsolidated material along the bottom. The turbulence generated in this process rapidly dissipates the energy of the current. Maximum estimated shear stress values were generated by the *Sugar Island* during disposal in 45 ft of water (Table 4). At a point on the ocean bottom, the shear stress arrives as a “surge” or "gust" of high velocity flow, which initially mobilizes bottom material that quickly settles to the bottom following its passage. The maximum estimated shear stress of 74 Pa is reached at a distance of about 15 m from the disposal centerline (*Sugar Island*, shallow dumps), dissipating to less than 10 Pa by a distance of 40 m (Figure 7). Dissipation is rapid: shear stress is less than 10 Pa within 1 min from the start of disposal and near 0 Pa in 2 min (Figure 8). Shear stresses generated by the *Essayons* were generally lower and dissipated even more rapidly, to less than 10 Pa within 15 to 20 m in less than 1 min (Figures 7 and 8). Shear stresses generated by deep-water dumps never exceeded 10 Pa (Table 4, Figures 7 and 8).

3.2.3 Mound thickness

The maximum predicted mound thickness of 12.6 cm (about 5 in.) was generated by the *Essayons* dumping in a 45-ft water depth under the no-slope condition (Table 4). Maximum mound thicknesses in the 8-cm to 11-cm range were predicted for the *Essayons* in 65 ft of water and for all shallow-water dumps by the *Sugar Island* (Table 4). The *Essayons* has a discharge volume of more than twice that of the *Sugar Island*, a slower discharge speed, and a longer discharge duration (Figure 9). These factors affect mound thickness, size, and shape (Figure 9). For the *Essayons*, the mound thickness is less for the longer discharge duration, as expected. Mound thickness was predicted to be no more than about 6 cm for any of the deep-water dumps by either dredge, although again, a thicker and larger mound is expected for the *Essayons* (Table 4, Figure 10). Predicted differences are also influenced by the ambient currents, which advect fine sediment during the descent phase of the disposal process.

3.2.4 Summary of STFATE Modeling of Expected Dredging Scenarios

The data show that predicted impact pressure, shear stress, and mound depth vary by type of dredge and are greatly reduced by discharge in deep water, and somewhat reduced at longer discharge duration. The *Essayons* data show that, at the same water depth, greater stresses are developed for the shorter discharge duration. The greatest compression and shear forces are developed by the *Sugar Island*, for which the discharge duration is only 3 min. Even though the *Sugar Island* is disposing less than half the total volume of the *Essayons*, it is traveling at a much higher speed during discharge. The comparison of mound thickness among the three discharge duration cases is not as simple, but the greatest mound thickness occurred in shallow (45 ft to 65 ft) water with the dredge discharging parallel to slope or where no slope was assumed.

4.0 Vulnerability Analysis: Potential Effects of the Disposal Process on Crabs

The disposal process produces a series of forces that may act upon Dungeness crabs, *C. magister,* present within the disposal site. The objective of the vulnerability analysis was to compare the values of the relevant forces derived from the modeling effort with what is known about crab biology to identify which physical processes are likely to lead to injury. Although the vertical impact, shear stress, and burial may interact to produce compounded effects, they will be discussed individually here to better understand the individual mechanisms and how they may affect crabs. Maximum values of each parameter for the particular discharge case (which predicted the highest impact pressure and shear stresses) are summarized in Table 5 for each dredge, water depth, and disposal duration. These data provide estimates of the stressor levels to which crabs might be exposed and were used in the vulnerability analysis.

4.1 Vertical Impact Pressure

The convective descent develops an impact pressure on the bottom that may injure crabs as a result of the vertical impact or compressive force. Little is known about what effect this force has on the crab. Determination of this effect is complicated by differences in shell strength with age and molting stage, firmness of the substrate, and crab behavior in response to the event. What little information is available in the literature suggests that the tensile strength and the Young's modulus for crab carapace material given in Wainwright et al. (1976) is many times greater than the vertical pressure developed during disposal. Tensile strength refers to how well material resists compressional force perpendicular to the surface. Young's modulus is a measure of elasticity of a material, how well the material returns to its original shape when a stress is relieved. The maximum predicted vertical pressure of 55,669 Pa was developed during the 3-min duration discharge from the *Sugar Island* in 45 ft of water while the vessel was moving perpendicular to the bottom slope (Table 4). The ultimate tensile strength of chitin from the carapace of the green crab, *Carcinus meanas*, is 32 million Pa, and Young's modulus of elasticity for *Cancer* sp. is 11 billion Pa (Wainwright et al. 1976). For hard-shelled crabs, the maximum compression force found in the modeled scenarios appears to be orders of magnitude below that which might fracture or deform crab carapaces in the hard-shell state. Wainwright et al. (1976) warns us that the crustacean carapace is a complex structure that has been little studied concerning its potential for failure, and that simple measures of strength may not be the most important factors concerning the resistance of crustacean exoskeletons to fracture or other injury. Essentially, Wainwright et al. (1976) suggests that the resiliency of an intact carapace may be even greater than that of component materials, i.e., chitin.

Shell-hardness studies conducted on *C. magister* in Alaska (Hicks and Johnson 1991, 1999) used an apparatus known as a Durometer to measure hardness, which is reported in what is known as the "Durometer hardness" scale. The hardness value is determined by the penetration of the Durometer indenter foot into the sample and provides a measure of the relative units of pressure (0 to 100 Durometers) that must be applied to result in an indentation of the surface. Hicks and Johnson (1991, 1999) used the Durometer to develop estimates of hardening of the carapace of adult crabs since time of molting. They reported that legal male crabs average 19 Durometers one month after molting, 46 Durometers at three months, and 66 Durometers at five months. Several scales exist for Durometer readings. The type of equipment used by Hicks and Johnson implies that the results were reported in

Shore Durometer D units. Assuming that to be the case, a comparative hardness of 19 Durometers is approximately that of basswood, 46 Durometers is about the same as urethane rubber, and 66 Durometers is somewhat harder than white pine and less hard than lead. The tensile strength of some materials has been related to the hardness (Brinell-HB scale), but this has not been done for crab carapaces. These hardness data also suggest that the crab carapaces are unlikely to be broken by the maximum compression forces predicted for the shallow-water, short-duration dumps. The use of Durometer measurements in future studies promises to provide more precise measurements of shell hardness than the presently-used scale based on visual and tactile observations.

Some catch-and-release studies do indicate that soft-shelled *C. magister* are much more fragile than hard-shelled crabs. In these studies, summarized in Kruse et al. (1994), the crabs were removed from the water and treated as they would be in a commercial sorting operation before being returned to the sea, whereupon nearly 40% were dead or moribund after 5 days. If handling were excessively rough or frequent (e.g., if the crabs were dropped on deck or handled multiple times), the mortality increased to 57%.

Recent studies suggest that studies of crabs removed from the water may substantially overestimate the mortality of crabs that remain in the water during and after molting. Studies with the blue crab, *Callinectes sapidus,* show that immediately after molting, the animal is capable of vigorous, rapid, and forceful movement (Taylor and Kier 2003). The animal is able to develop sufficient rigidity for muscle resistance by increasing the hydrostatic pressure within the newly formed carapace. Within 12 hours after molting, the shell is noticeably more rigid than during the "paper shell" stage, and within 2 to 3 days, the new shell has hardened substantially. These observations, albeit for a different crab species, suggest that we cannot assume that a soft-shelled crab in the water is more vulnerable to the relevant forces from a disposal event than is a hard-shelled crab. The situation may not be simple because the flexibility of the soft shell may effectively absorb impacts, and the behavior of the crab may allow it to avoid damage. The influence of these factors has not been specifically studied.

In summary, the study by Wainwright et al. (1976) warns us that the crustacean carapace is a complex structure that has been little studied concerning its potential for failure, and that simple measures of strength may not be the most important factors concerning the resistance of crustacean exoskeletons to fracture or other injury. Presently, there are no experimental data specific to crabs that indicate the threshold at which compression or impact force will fracture or deform an intact carapace or produce other injury in a crab. However, the available information suggests that injury from compression forces is less likely than injury from the other two stressors considered next.

4.2 Horizontal Shear Stress

The size of material that could be mobilized by horizontal shear stress depends on the material density and the magnitude of the shear stress. Criteria for the initiation of motion for river flows (unidirectional flows) have been developed that relate the near-bottom shear stress to the size of material that would be dislodged from the bed (Miller et al. 1977); some examples are provided in Table 6. Based on these criteria, the maximum predicted shear stress generated by an expected Columbia River disposal scenario of 74 Pa from disposal by the *Sugar Island* in 45-ft water depth could move a rock that is 8.2 cm in diameter, about the size of a baseball or a juvenile 1+ Dungeness crab. In contrast, the 0.59 Pa generated by an *Essayons* 14-and 9-min dumps in 280 ft of water is sufficient to mobilize granular sediment of <1 mm diameter.

Shear stresses were related to horizontal current by using the methods of Miller et al. (1977). For the maximum predicted 74 Pa shear stress, the estimated bottom current velocity was 4.13 m/s. The range of expected bottom velocities estimated by applying the methods of Miller et al. to the STFATE horizontal shear-stress estimates is provided in Table 5; as expected, the lowest current velocities (<1 m/s) occurred with deep-water disposal. These estimates of the effect of the shear stress on the bottom and the developed current are based on steady-flow conditions that are only approximated during the disposal process. There are no data available that can be used to confirm horizontal shear stress and currents generated by the complicated conditions developed in the actual disposal event at the Columbia River disposal sites. However, some information to partially address potential effects from dynamic collapse is available from the Palos Verdes (California) disposal study. Studies of the Palos Verdes disposal site were undertaken to determine the extent to which disposal would erode sediment from the bottom by inducing a bottom surge current that would transport material a significant distance from the disposal location (Bratos et al. 2002, McDowell et al. 2002). *In-situ* measurements of surge currents of six experimental disposal events at Palos Verdes demonstrated that surge currents between 0.75 m/s and 1.36 m/s occurred at 75 m downslope from the disposal location (Bratos et al. 2002, McDowell et al. 2002). Surge currents at the disposal location could have been higher, but to what extent is unknown.

The occurrence and extent of shear current impacts on Dungeness crabs depend on whether the crabs are burrowed (or partially burrowed) or on the surface and how the crabs respond to the impulse of the increased shear stress. Crab age and molting stage probably are also factors. Studies of the behavior of the amphibious shore crabs *(Grapsus tenuicrustatus)* in Hawaii indicate that the effect of the current on a shore crab depends, among other factors, on the magnitude of the current, the crab's orientation to it, and the response of the crab. The predicted maximum current generated by the *Sugar Island* discharging in 45 ft of water is 4.13 m/s (Table 5), corresponding to 8.13 knots. Martinez (2001) determined in laboratory experiments with shore crabs (*Grapsus tenuicrustatus*) that the critical water velocity required to wash away a crab was 5.72 m/s and the critical velocity to overturn the crab was 8.20 m/s. The shore crab is an intertidal species that is exposed to wave-swept environments and relatively strong oscillatory currents caused by wave swash. It has a higher stance on land than in water and uses posture and orientation to the ambient current to maintain stability in the flow. The shore crab also is capable of clinging to the substratum (e.g., active tenacity), and, for rough rocky substratum, the crab can withstand considerable current. Without rough rocky substratum, a current speed of only 0.25 m/s was sufficient to wash shore crabs away. The estimated bottom velocities estimated from modeled maximum shear stress values are within the range of 0.25 m/s to 5.72 m/s critical velocities reported by Martinez (2001).

The hydrodynamic force on the crab affects the force the animal must exert to move and determines whether the animal washes off the substrate or overturns. Few studies address the stability of aquatic animals under such hydrodynamic forces, and none could be found for *C. magister*. The hydrodynamic forces on an animal are not prescribed simply by the water-flow environment, but are also modified by the animal's reaction to the flow. The animal may adopt a different posture in response to the flow, thereby changing the magnitude or even the direction of the relative lift force; it may burrow into the sediment; or the crab may swim to move with the current (however, swimming ability in the Dungeness crab is limited). It is true that dislodgement from the substratum is a serious problem for pedestrian animals, such as *Grapsus tenuicrustatus* and *C. magister*, because they must maintain contact with the substratum to generate thrust. With sufficient hydrodynamic force, the animal may be dislodged and overturned or washed away. If the substratum is unconsolidated sediment that is set in general motion by the hydrodynamic shear stress, the animal may become part of that motion even if it is fully or partially burrowed.

To place the magnitudes of the predicted shear stresses into perspective in another way, the estimated bottom velocity values were compared with benthic conditions created by natural waves. The Oregon coast is often swept by storms that generate large waves. These most often occur during the winter months when the average significant wave height is 3 m and the average wave period is 12 s; in summer months, waves average 1.5 m with 8-s periods (Ruggiero et al. 1997). During large storms, wave conditions can become spectacularly severe, as in the El Niño storm of January 17, 1998, when significant wave heights of 14.52 m with 22 s periods were recorded at the Grays Harbor wave buoy. Prior to this event, peak significant wave heights were above 7 m with 20 s periods for 6 h (Kaminsky et al. 2000). The wave buoy at the Columbia River entrance also recorded a wave height of 7.8 m and a peak period of 17.4 s during this period.

Based on long-term wave measurements along the Columbia River littoral cell, which extends from the MCR to approximately Cape Elizabeth, Ruggiero et al. (1997) determined that the 50-year wave height (e.g., that wave height that has a 2% chance of occurring during any given year) ranges between 8.5 m and 12.2 m. This range is apparently due to measurement differences of the wave buoys and does not appear to be associated with a north-south trend along the coast. Other studies by Moritz and Moritz (2002) indicate that the 100-year wave height near the MCR is 12.4 m.

The wave-generated, near-bottom currents that would occur for the approximate 50- and 100-year wave conditions at the four disposal depths of this study were calculated using linear wave theory. The 50-year wave condition was selected as 10 m, the approximate average of the range given by Ruggiero et al. (1997); wave periods of 12 s and 15 s were used to characterize long-period storm waves. The 100-year wave height was selected as 12.4 m after Moritz and Moritz (2002). The maximum magnitudes of the resulting orbital currents are given in Table 7.

The expected bottom velocity generated by the disposal event are comparable to the bottom orbital velocity generated by the 50- and 100-year storm events (Table 7). As would be expected, the highest velocities for the conditions evaluated occur in the shallowest water (45 ft). The highest bottom velocity expected during the disposal process (4.13 m/s) is developed by the *Sugar Island* in a 45-ft water depth and is comparable with the orbital current velocity from a 32.8-ft, 15-s (50-year return) wave in the same water depth. The wave-height calculation is based on the significant wave height, defined as the average of the largest one-third of the waves in the wave field. This means that waves greater than 32.8 ft will occur, along with greater orbital currents, and that waves greater than 38 ft will break in 45-ft water depth.

In summary, circumstantial evidence is provided through 1) the range of bottom currents predicted from STFATE output of Columbia River disposal scenarios, 2) surge-current measurements from Palos Verdes disposal events, and 3) the sediment mobilization analyses using Miller et al. (1977) to reasonably hypothesize that surge currents during the dynamic-collapse phase of some disposal events may be capable of eroding at least juvenile Dungeness crabs from bottom sediment. This vulnerability to surge currents pertains to the shallow water scenarios. The surge currents in the deep water scenarios do not appear to be strong enough to mobilize juvenile crabs. Further, behavioral responses by the crabs could reduce the occurrence and extent of injury from such movement by surge currents. Present information leads to hypothesize that crabs are vulnerable to injury from surge currents; however, the available information is not sufficient to confirm or deny the hypothesis that surge currents from some disposal events can adversely affect Dungeness crabs.

4.3 Mound Thickness – Burial

Direct burial by dredged materials discharged in large quantities within the short interval of an operation is the most obvious dredging impact on benthic organisms (Morton 1976, Maurer et al. 1981). Though burial is a potentially important impact, reports from various monitoring programs clearly demonstrate that the level and scale of impacts are related to a number of attributes of the dredge-disposal event, the receiving habitat, and the community composition at the disposal site (Smith and Rule 2001, Germano and Cary 2005). In a series of experiments conducted in laboratory tanks and aquaria, Maurer and colleagues documented the vertical migration of various taxa of organisms through sediment that was configured to represent dredged materials (Maurer et al. 1980, 1981, 1982, and 1986). Only one crab species, *Neopanope sayi,* was observed in this experiment. This small crab (maximum carapace width ranged from 2.0 cm to 2.5 cm) was able to migrate vertically through at least 32 cm (12.6 in) of sediment to the surface. In pilot studies, Maurer et al. (1981) observed that several individuals were able to migrate through 85 cm of fine sand. Field studies by Roberts et al. (1998) indicated that a maximum thickness of 15 cm, instantaneously applied, allowed benthic fauna the opportunity to migrate through the overburden. Benthic organisms examined by Roberts et al. (1998) included amphipods and bivalves, but not crabs.

Concerning the Dungeness crab, it is important to understand that burrowing into the sediment is a natural and normal behavior for the crab and that the respiratory system of the crab is adapted to burrowing. When buried naturally, Dungeness crabs establish a respiratory current with the overlying water to enable oxygen-bearing water to be drawn over the crab's gills. MacKay (1942) and McGaw (2005) provide descriptions of burrowing behavior by Dungeness crabs. The bottom type favored by Dungeness crabs is sand or mud-sand substrates. In sandy intertidal beaches, crabs that are stranded by the receding water may burrow by backing into the loose sediment for protection, leaving only interstitial water available for ventilation of the gills. The oxygen level in the interstitial water is quickly depleted and the crabs must be adapted to survive under low-oxygen conditions. Estuarine sediment and waters above them also may be hypoxic, and the crabs must survive in this depleted environment for at least a tidal cycle (Airriess and McMahon 1994). In deeper water, Dungeness crabs also burrow during the soft-shell stage or during periods of inactivity. The precise function for burrowing is not known, but predator avoidance, prey capture by ambush, and energy conservation have been suggested (McGaw 2004, 2005).

Dungeness crabs are “back burrowers” in that they back into the soft sediment, leaving only their antennae and eyestalks exposed (McGaw 2004, 2005). Following active burrowing, which usually takes about 30 s to be completed, physiological changes occur, such as decreased heart rate and occasional cessation of gill ventilation for up to 30 min. Avoiding clogging of the ventilatory intake openings is achieved by shifting the body to loosen the sand and allow water flow through the brachial chambers, and by reversing the water flow through branchial chambers, even while completely burrowed. The underside of the carapace of *C. magister* is also covered with setae, which could function in maintaining a pathway for water delivery to the ventilatory openings. In the open ocean, in clean sediment, oxygen is not limiting for animals burrowed into sand; McGaw (2004) reports that individual crabs remained buried for an average of about 4 h and for a maximum of more than 50 hours. During the winter, ovigerous female *C. magister* may remain burrowed for up to 2 weeks (McGaw 2005). The key factor enabling Dungeness crabs to remain burrowed for long periods is the maintenance of the respiratory pathway to oxygen-bearing water, and burial effects from disposal may depend on maintenance of the respiratory pathway when crabs are buried.

Three studies have attempted to determine the effects of direct burial by dredged materials on Dungeness crabs. In the first, Chang and Levings (1978) simply introduced dredged sand into 45-cm diameter pails or oval tanks (64 cm by 45 cm) that contained adult male Dungeness crabs. The molting stage was not specified but was presumably hard-shelled. For burial depths of 5 cm and less, all crabs were able to re-establish respiratory currents to the overlaying water within 6 hours (Chang and Levings 1978). For a burial depth of 10 cm, crabs did not re-establish a respiratory current but emerged from burial within 24 hours. For a burial depth of 20 cm, crabs did not re-establish a respiratory current, and only 2 emerged from burial within 24 hours. Crabs buried for 24 and 48 hours were recovered alive, but crabs buried for 120 hours were recovered dead.

The second study was performed at Scripps Institute of Oceanography using adult hard-shelled crabs placed in a 3- by 0.6- by 1.8-m deep tank with a layer of sand on the bottom (USACE 1999). Crabs were allowed to bury themselves before wet or dry sand was released from a louvered dump box designed to mimic the duration of typical disposal events. In experiments during which 21 cm (0.7 ft) of sand was deposited over the full width of the tank, about 75% of the crabs emerged from burial within 1 hour. In one experiment in which 25.5 cm (0.85 ft) of sand was deposited as a mound in the center of the tank, 100% of the crabs emerged from burial within 1 hour. Among crabs that emerged, there was no mortality over the several weeks following the experiments. Crabs that remained buried did suffer mortality, but the rate and time frame were not clearly reported.

The third study by Antrim and Gruendell (1998) examined the responses of three size-classes of Dungeness crabs, *Cancer magister*, and graceful Cancer crabs, *Cancer gracilis*, to burial by sand in cylindrical tanks 53 cm in diameter and 43 cm deep. Hard- and soft-shelled crabs were tested, but not for all burial depths. For all burial depths tested between 6 cm and 26 cm, the mean survival rates were 85% for Age 0+, 52% for Age 1+, and 50% for adult crabs. The patterns of survival by depth also differed by age class. All crabs that remained buried for 72 to 96 h were recovered dead. For the Age 0+ crabs, survival was above 75% at all burial depths. For the Age 1+ crabs, survival decreased to about 60% at 12-cm burial depth and from 40% to 50% at burial depths >17 cm. Survival of adult crabs decreased from 100% at 12-cm burial depth to <30% at 17-cm burial depth and above.

The Age 0+ crabs were recently molted, presumably more susceptible to injury, and therefore, not expected to have the highest survival rate. The behavioral response of the crabs varied with age class. Age 0+ crabs were more active and more readily emerged from burial at the start of disposal. Also, the neutral buoyancy of the Age 0+ crabs enabled them to be readily lifted by water currents. Antrim and Gruendell (1998) stated that their experiments were too preliminary to draw any conclusions, primarily because the size and configuration of the test chambers allowed no opportunity for the crabs to actively escape the descending sand through the crab's normal horizontal movements. Thus, the results of Antrim and Gruendell (1998) suggest that crab behavior during the disposal event may substantially influence crab survival and may be a factor comparable with crab size or depth of burial. The difference in results between the Scripps study (USACE 1999) and Antrim and Gruendell (1998) may be related to the fact that the Antrim and Gruendell study provided little or no opportunity for escape response whereas the large tanks and disposal patterns of the Scripps study did provide some opportunity for escape behavior.

The studies clearly indicate that Dungeness crabs can respond to falling sand and to burial, but the previous studies are problematic in several ways. First, the small sizes and configurations of the test did not allow the full range of behavioral responses. Second, the test-chamber configurations did not allow full development of surge currents, thereby precluding crabs from responding to associated disposal conditions with appropriate escape behavior. Third, dry sand drawn from commercial sources may not fully mimic sand drawn from the marine environment of interest. Thus, the results of the presently available experiments indicate a vulnerability to burial, provide a rough estimate of what burial depths might influence survival of the crabs, but do not indicate how escape behavior might reduce crab exposure to surge currents and burial.

4.4 Summary of Relevant Stressors and Vulnerabilities

The analysis of numerical modeling results and vulnerabilities indicate that the vulnerability of crabs to compression forces under any of the disposal scenarios is low but can not be completely discounted. Modeling results and other information suggest that vulnerability of crabs to injury from surge currents may occur under some but not all disposal scenarios. For the deep-water disposal scenarios, the maximum forces and mounding heights are substantially less than those for the shallow water scenarios. The surge currents estimated from modeling the deep water scenarios were not strong enough to mobilize sediment greater than 1 mm or juvenile Dungeness crabs. For the shallow-water, short-duration disposal scenarios, the shear stress and surge currents estimated from the modeling and observed in the field at Palos Verdes appear to be sufficiently high to mobilize and transport the bottom sediment and at least juvenile crabs. The effects of such movement, if any, are not known. Behavioral response to surge currents probably occurs and may reduce the occurrence and extent of movement and any associated impacts. There is evidence that crabs may be vulnerable to burial through effects respiration and survival. Loss of the respiratory pathway is a key factor in burial effects. For burial with 10 cm and greater depths, Dungeness crabs were unable to recover the respiratory pathway and switched to moving up through the sediment, a process that occurred over 24 hours. The observation that crabs can take some hours to emerge after burial suggests that multiple dumps over the same area would increase vulnerability. In most cases, the standard disposal practice is to not dump sequentially at the same location but to systematically spread the dumps over the whole of the disposal site. It is clear that crab behavior reduces vulnerability, but to what extent is much less clear. There are differences in the results for the Scripps study (USACE 1999) and the Antrim and Gruendell (1998) study at the same burial depth that may be related to tank size, disposal methods, and the opportunity for escape behavior. Two questions concerning burial remain. First, if no escape response is permitted, what is the threshold for effects for each age class and molting stage? Second, if escape response is permitted in a realistically designed disposal simulation, to what extent do escape and other behavioral responses reduce exposure to the relevant stressors and the subsequent impacts?

5.0 Recommended Experimental Approach to Estimating Effects of the Disposal Process on Crabs

Examination of the vulnerabilities enables us to offer a prioritized list of study questions for Phase 2. These questions in order of highest priority are as follows:

1. If no escape response is permitted, what is the threshold for effects from burial for each age class and molting stage?
2. If escape response is permitted in a realistically designed disposal simulation, to what extent do escape and other behavioral responses reduce effects from burial?
3. What is the threshold for effects from mobilization and transport by surge currents?
4. To what extent do escape and other behavioral responses reduce surge-current effects?
5. To what extent does exposure to surge currents influence the occurrence and extent of effects from subsequent burial?

Based on the low vulnerability of crabs to compression forces that are orders of magnitude less than the strength of chitin, we recommend that studies of compression forces be given a low priority. We also recommend that field studies of the disposal process to validate the model results be given a low priority. First, the STFATE model has been refined over many years to enhance the accuracy with which it predicts mound thickness. The costs of further studies to validate mound predictions do not appear warranted given the greater uncertainties associated with other aspects of assessing disposal effects. Second, the model results for surge currents are quite comparable with the *in-situ* measurements from the Palos Verdes study and are sufficient to set the experimental conditions for laboratory studies. There is much more uncertainty about the extent to which surge currents would move crabs and about the potential effects of such movement. We suggest that effort be directed to address the larger uncertainties associated with surge currents.

The disposal scenarios that should be the focus of Phase 2 studies are clearly those for shallow water and short duration. Once threshold values are determined with simulations of the maximum values likely to be attained in realistic disposal scenarios, the potential effects for the other scenarios in deeper water or longer duration can be modeled. The surge currents of interest range from 0.5 m/s to 5 m/s.

The five priority study questions involve processes that are interlinked in the disposal process. We suggest that because of interlinking, the questions are best addressed in a mesocosm that can simulate the relevant aspects of the disposal process, specifically the surge currents and mounding. A tower or jet can be used to introduce sediment slurries in a manner that mimics surge currents, followed by sediment deposition and mounding. Observation of crab behavior in the turbid conditions that will certainly follow the sediment introduction could be accomplished potentially in two ways. Acoustic tags can provide continuous positioning information and with refinements, perhaps also the burial or burrowed states of the crab. Using sound rather than light, the Dual-frequency Identification Sonar (DIDSON) camera was developed specifically to provide video-like images in turbid water. With a mesocosm, experiments can be designed to clearly separate burial effects when no escape response is permitted from those in which escape response is enabled. By scheduling experimental trials to time periods when crabs are active or inactive and buried, the influence of activity or burrowing state can be examined.

To gain population-level perspective on any effects determined from the laboratory studies would entail Adult Equivalent Loss (AEL) estimates, which were used by Pearson et al. (2002, 2003, 2005) to provide the same perspective for crab losses from dredge entrainment. The steps involved are illustrated in Figure 11. The models to predict the forces now exist. A bioassay model that provides mortality estimates as a function of stressor level would be developed from the laboratory experiments above. The demographic model can be supported in large part by existing crab population data on crab density, sex ratio, and age composition taken from studies such as Williams et al. (2004). Only limited data are available on the timing and amount of crab burrowing and on immigration and emigration rates. Some focused field studies may be needed after the laboratory studies to gather the most relevant crab data. The AEL model that exists now for entrainment losses can be easily modified for the application intended here. The integration of the series of models will enable estimation of the population-level impacts of disposal of dredged materials on Dungeness crab.

6.0 Figures and Tables

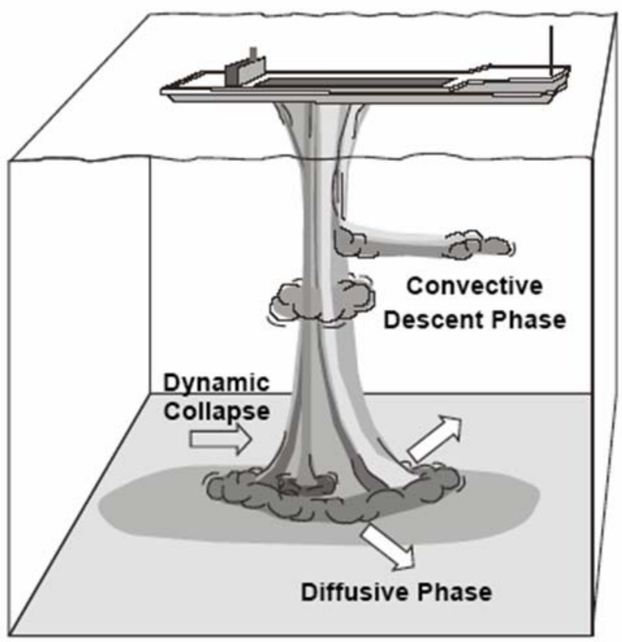

Figure 1. Phases of the Disposal Process Following Release from Dredge

Figure 2. Sidearm Hopper Dredge *Essayons*

Figure 3. Trailing Suction Hopper Dredge *Sugar Island*

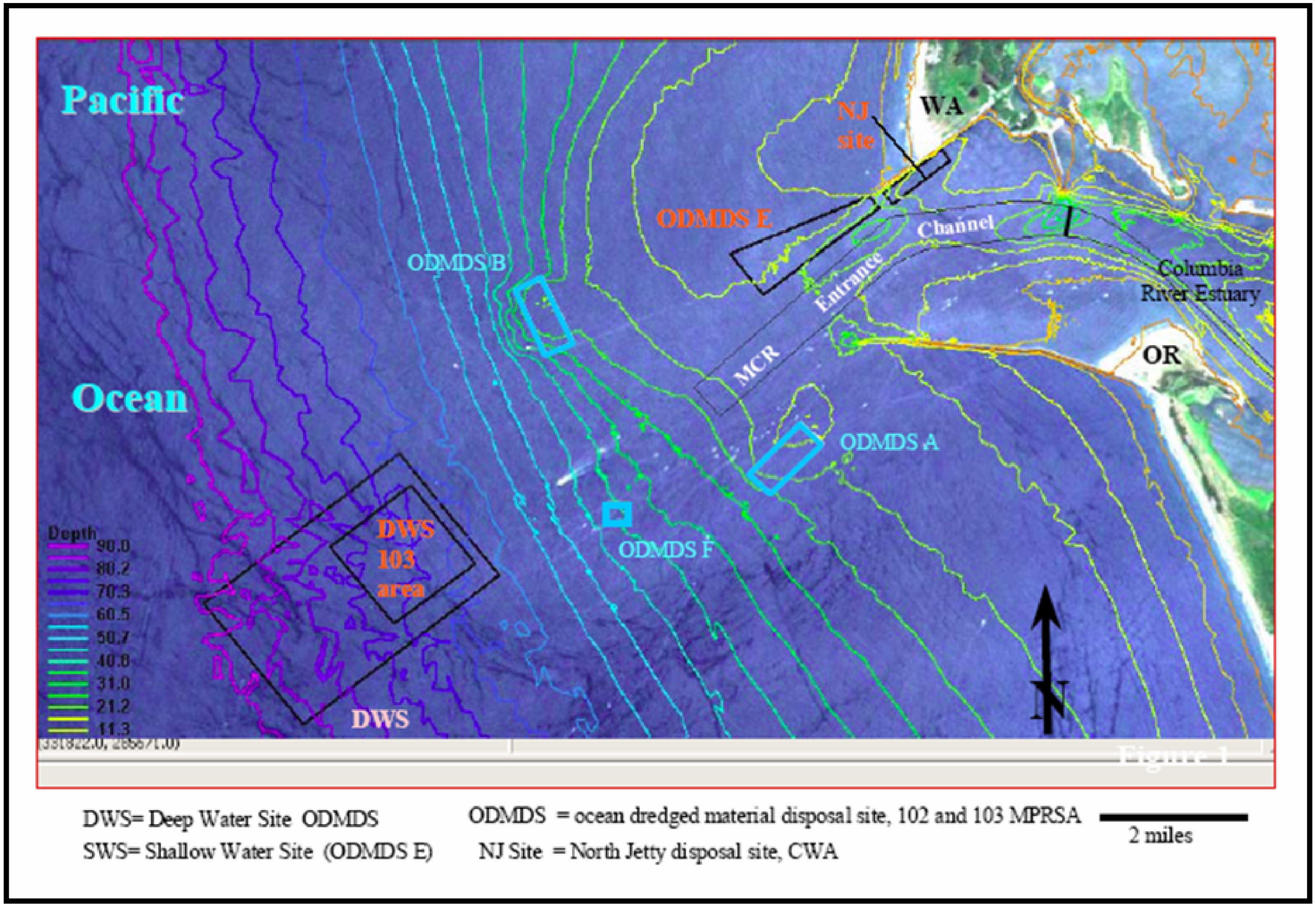

Figure 4. North Jetty and Ocean Dredged Material Disposal Sites

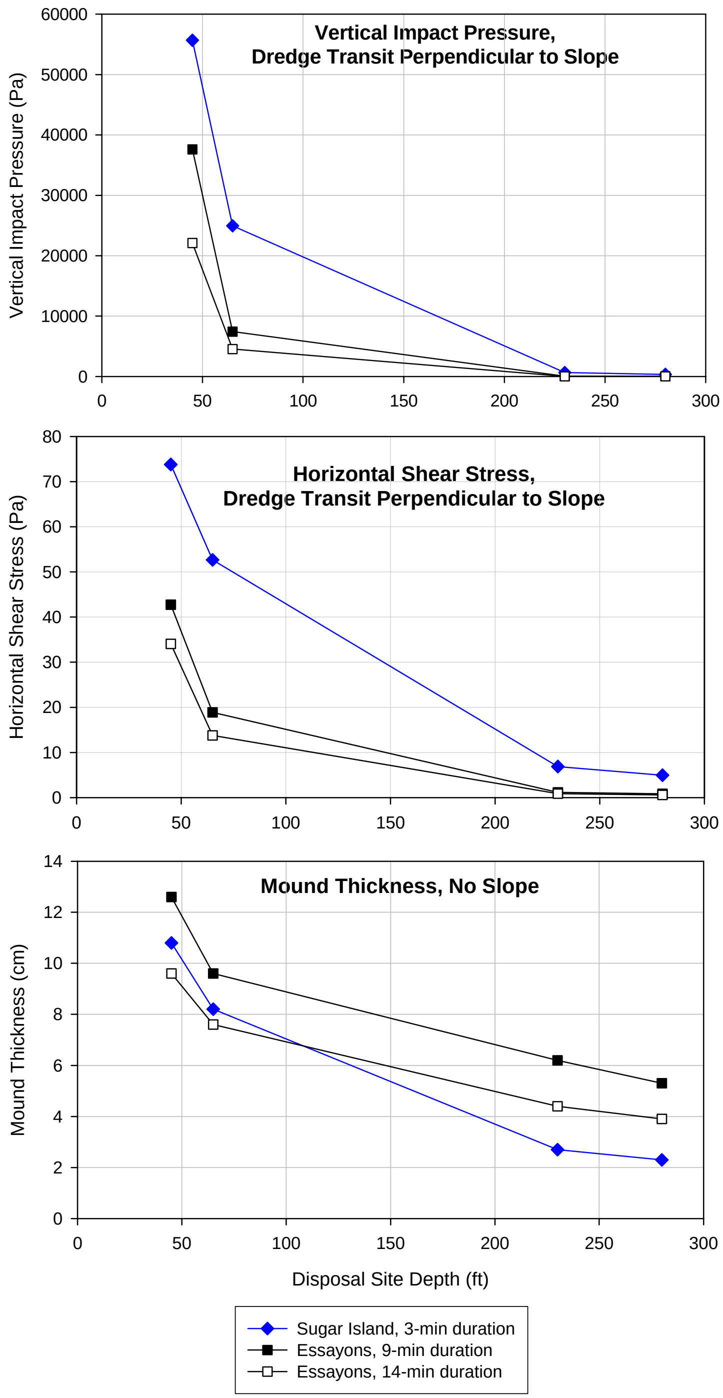

Figure 5. Maximum Vertical Impact Pressure, Horizontal Shear Stress, and Mound Thickness Estimated by STFATE for Each Scenario

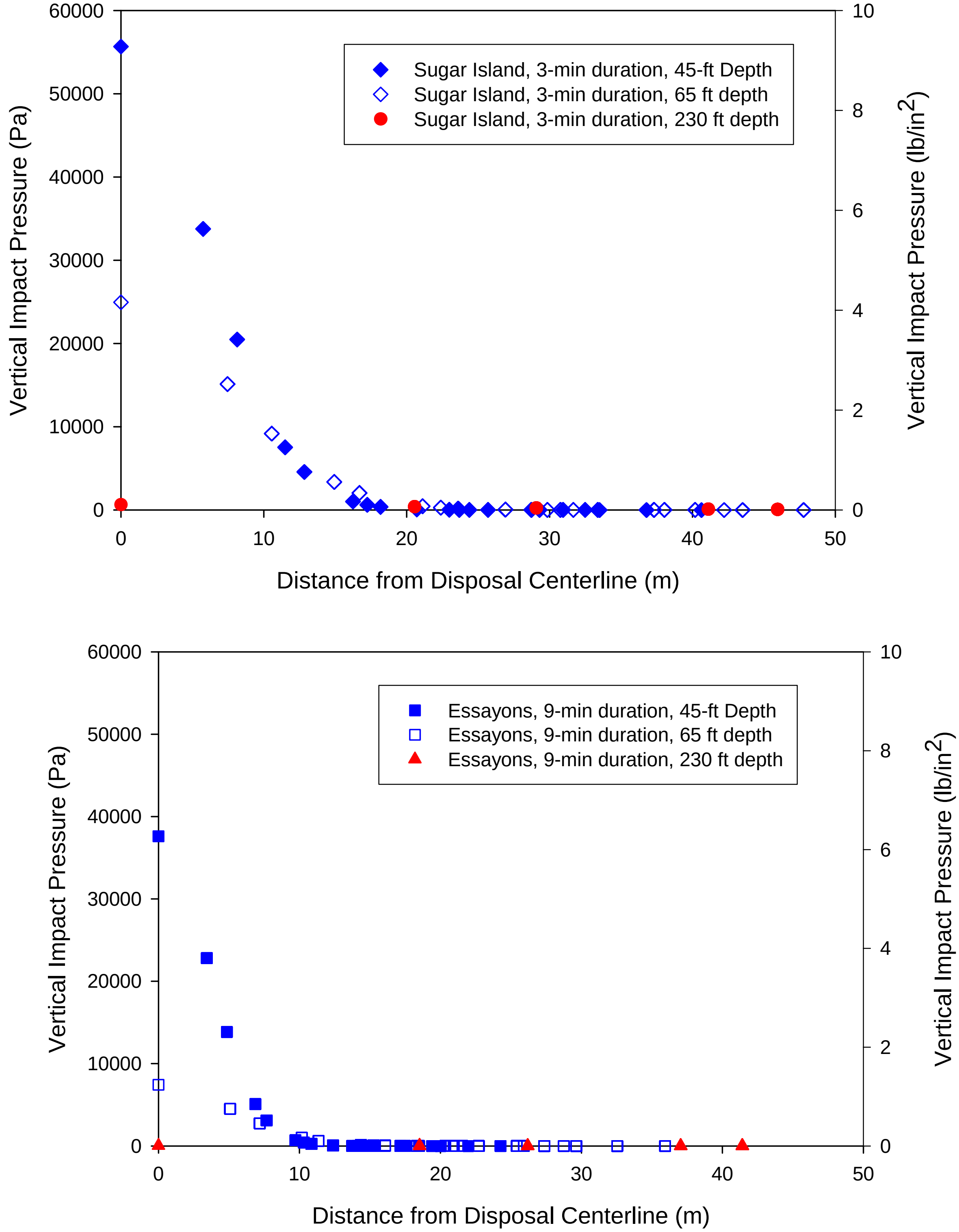

Figure 6. Modeled Estimates of Vertical Impact Pressure from Disposal in Various Water Depths by Hopper Dredges, *Sugar Island* (top) and *Essayons* (bottom)

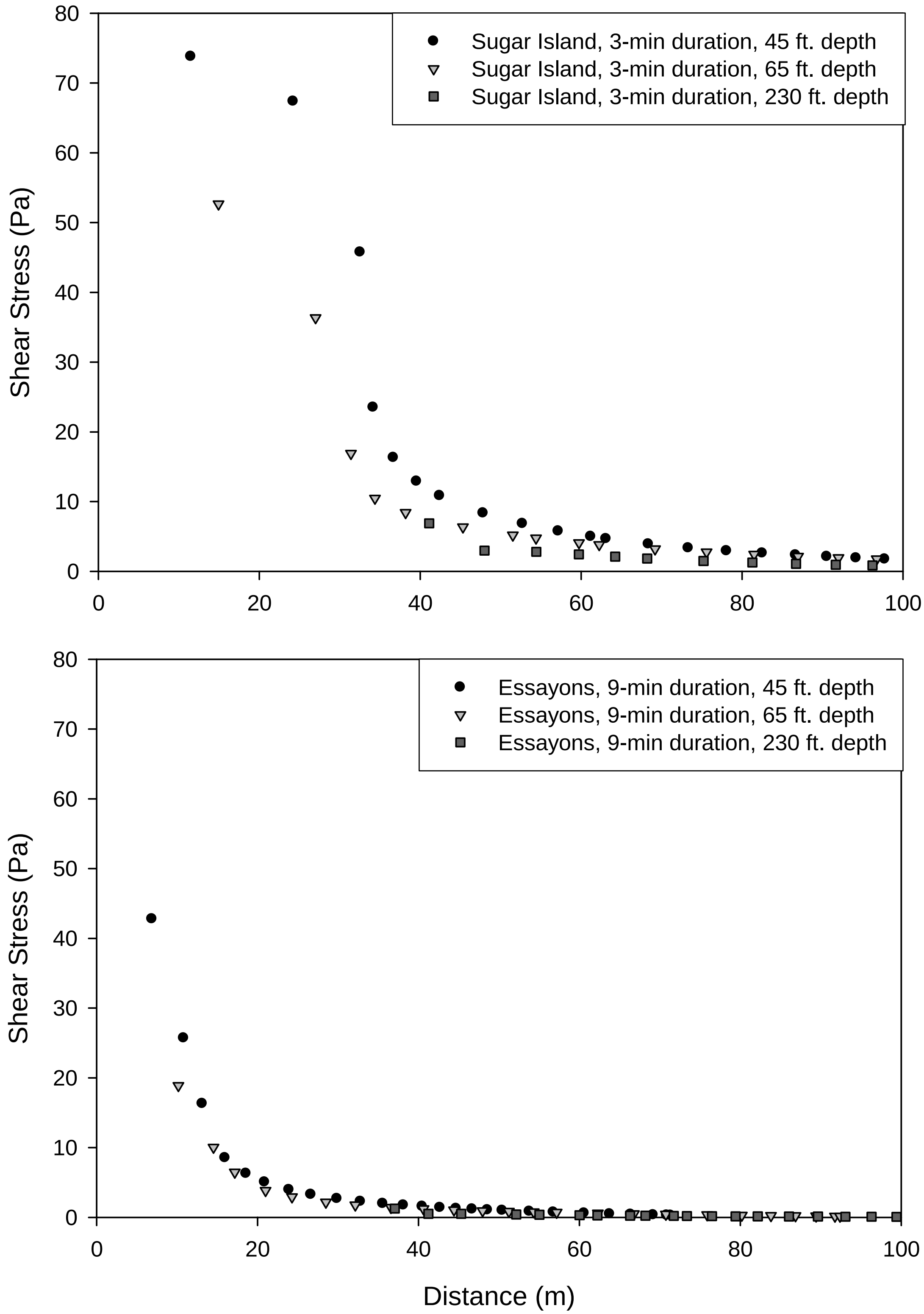

Figure 7. Horizontal Shear Stress with Distance from the Disposal Centerline During Disposal at Various Depths by the Hopper Dredges *Sugar Island* (top) and *Essayons* (bottom)

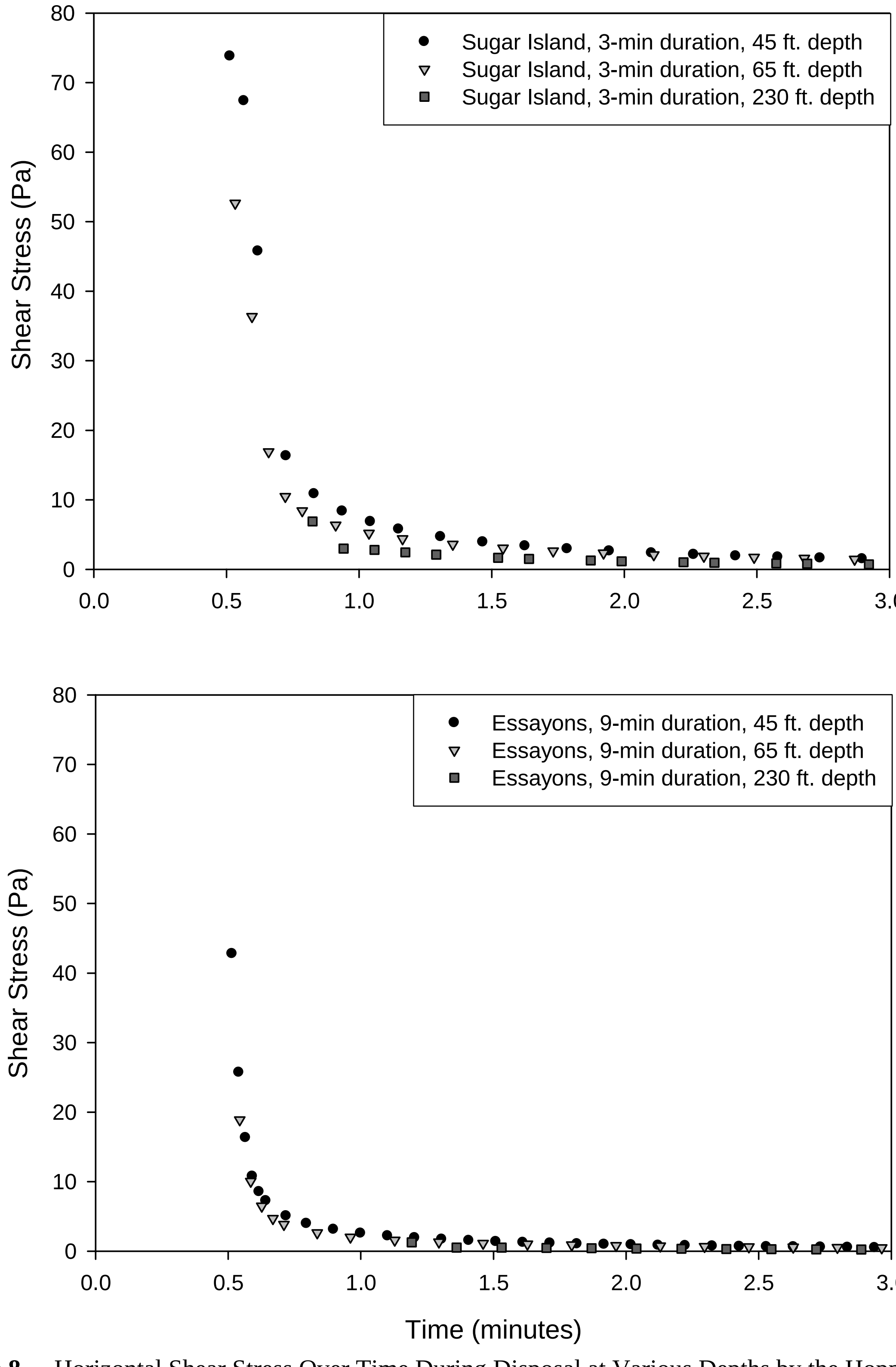

Figure 8. Horizontal Shear Stress Over Time During Disposal at Various Depths by the Hopper Dredges *Sugar Island* (top) and *Essayons* (bottom)

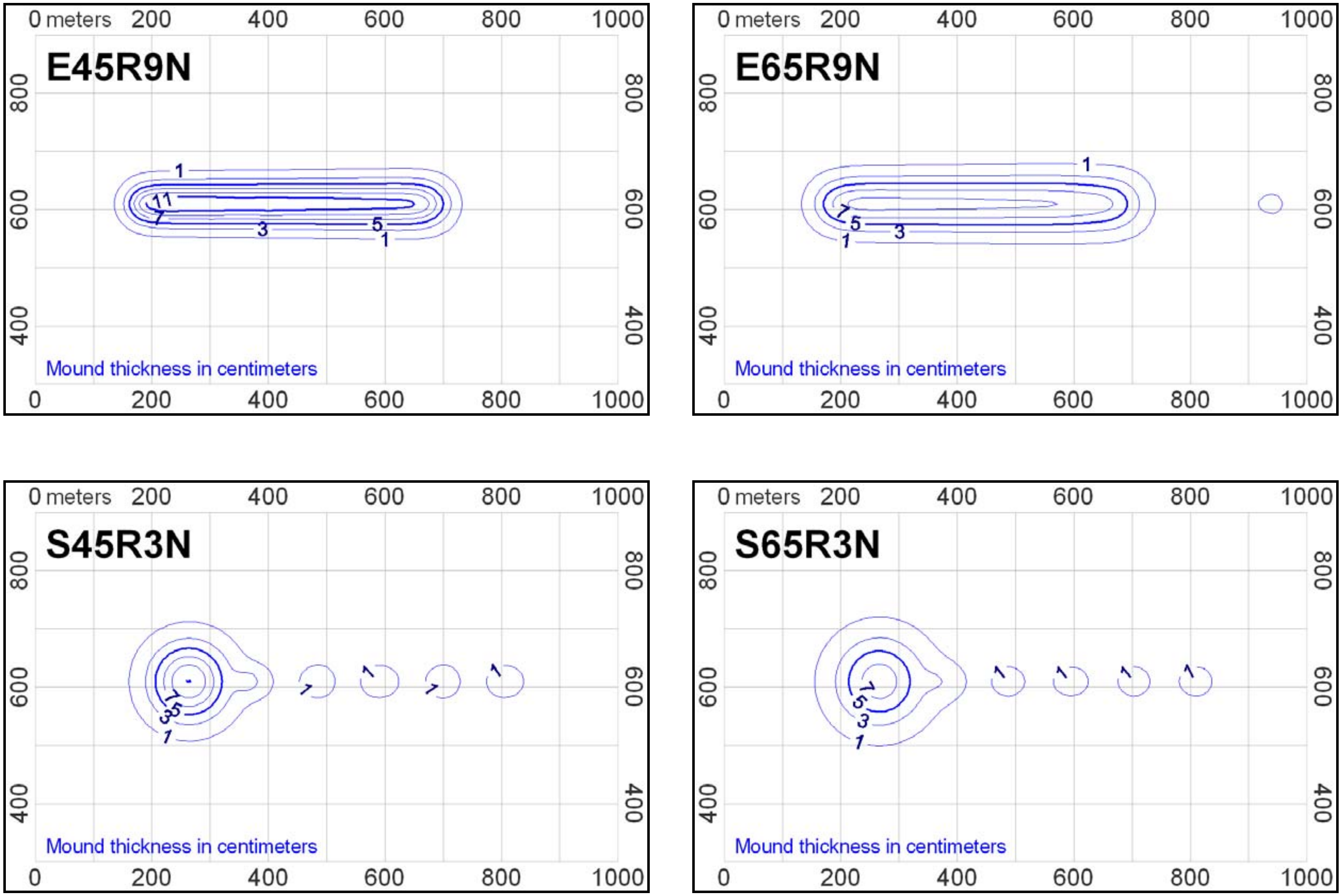

Figure 9. Modeled Mound Thickness for Short Discharge Duration in Shallower Water (top, *Essayons* 9-min discharge in 45 ft and 65 ft of water; bottom, *Sugar Island* 3-min discharge in 45 ft and 65 ft of water)

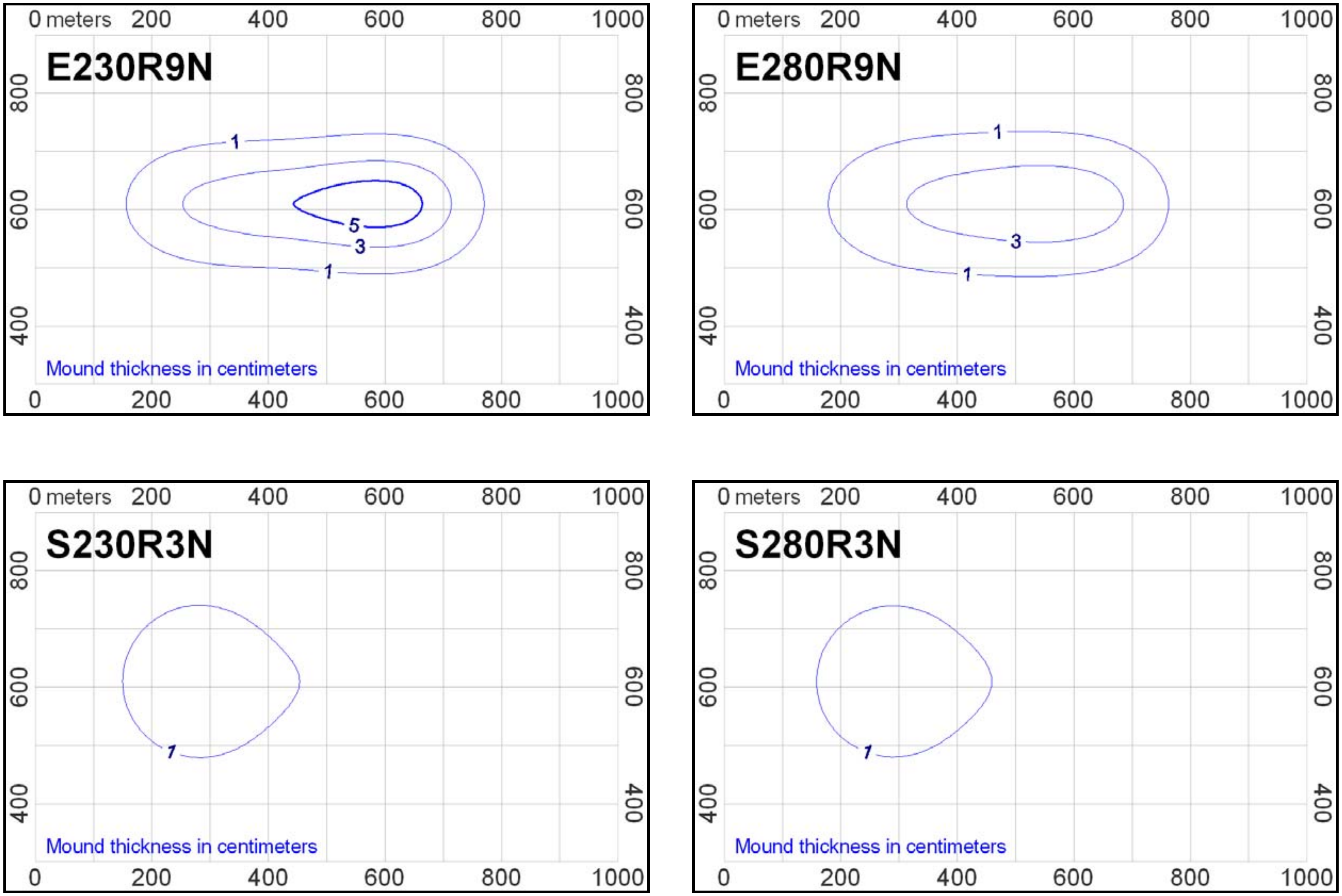

Figure 10. Modeled Mound Thickness for Short Discharge Duration in Deeper Water (top, *Essayons* 9-min discharge in 230 ft and 280 ft of water; bottom, *Sugar Island* 3-min discharge in 230 ft and 280 ft of water)

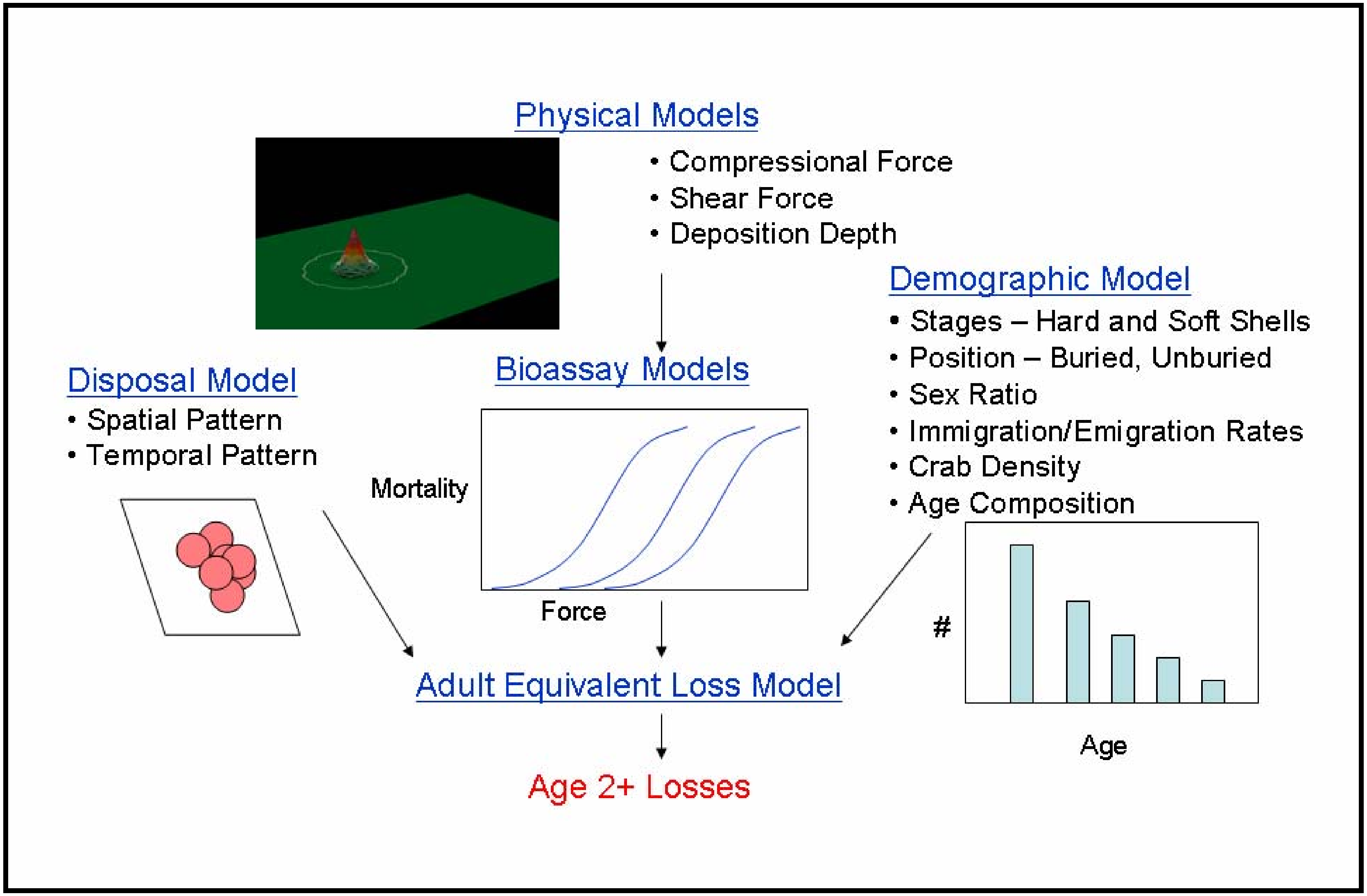

Figure 11. Integration of Models for Estimating Crab Mortality from Disposal

Table 1. Initial Conditions Modeled Using STFATE in Phase 1 Studies, 2003

Vessel	Water Depth (ft)	Vessel Speed (kt)	Discharge Rate (min)	Sediment Type
Newport	40	0	3	Columbia River
	50	3	8	
	70	6		
	120			
	200			
1	5	3	2	1
Number of cases modeled = 1x5x3x2x1 = 30				

Table 2. Summary of Modeled Scenarios for the Corps Dredge *Essayons*

Vessel	Water Depth (ft)	Vessel Speed (kt)	Discharge Duration[d] (min)	Slope Conditions	Current[a], (ft/s)	Sediment Type[b]
Essayons[c]	45	2	9, 14	No slope, Parallel to slope, Across slope	2	MCR, 2000 Table 1 Mean
	65					
	230				1	
	280					
1	4	1	2	3	1	1
Total Number of Cases = 24						

a. In all cases, current is uniform from surface to bottom and is in the same direction as ship motion.
b. Sediment grain sizes and distributions were supplied by the Portland District Corps from "Mouth of the Columbia River, Sediment Evaluation" (USACE 2000).
c. Load is considered to be 5500 cy of material.
d. Discharge durations were selected in whole minutes between 8-11 min and 12-15 min.

Table 3. Summary of Modeled Scenarios for the Dredge *Sugar Island*

Vessel	Water Depth (ft)	Vessel Speed (kt)	Discharge Duration (min)	Slope Conditions	Current[a], (ft/s)	Sediment Type[b]
Sugar Island[c]	45	7	3	No slope, Parallel to slope, Across slope	2	MCR, 2000 Table 1 Mean
	65					
	230				1	
	280					
1	4	1	1	3	1	1
Total Number of Cases = 12						

a. In all cases, current is uniform from surface to bottom and is in the same direction as ship motion.
b. Sediment grain sizes and distributions were supplied by the Portland District Corps from "Mouth of the Columbia River, Sediment Evaluation" (USACE 2000).
c. Load is considered to be 2500 cy of material.

Table 4. STFATE Inputs and Outcomes for Expected Dredging Scenarios

STFATE Modeled Scenarios, Input Conditions							Maximum Value for Scenario		
Vessel	**Depth (ft)**	**Speed (kn)**	**Discharge Duration (min)**	**Bottom Slope Condition**	**Current (ft/sec)**	**Sediment Type**	**Vertical Impact Pressure (Pa)**	**Horizontal Shear Stress (Pa)**	**Mound Thickness (cm)**
Essayons	45	2	9	None	2	MCR	29580	42	12.6
Essayons	45	2	9	Perpendicular	2	MCR	37611	43	11.9
Essayons	45	2	9	Parallel	2	MCR	31703	43	12.4
Essayons	65	2	9	None	2	MCR	6761	19	9.6
Essayons	65	2	9	Perpendicular	2	MCR	7427	19	9.3
Essayons	65	2	9	Parallel	2	MCR	6958	19	9.7
Essayons	230	2	9	None	1	MCR	35	1	6.2
Essayons	230	2	9	Perpendicular	1	MCR	36	1	6.1
Essayons	230	2	9	Parallel	1	MCR	36	1	6.0
Essayons	280	2	9	None	1	MCR	13	1	5.3
Essayons	280	2	9	Perpendicular	1	MCR	13	1	5.3
Essayons	280	2	9	Parallel	1	MCR	13	1	5.2
Essayons	45	2	14	None	2	MCR	21024	33	9.6
Essayons	45	2	14	Perpendicular	2	MCR	22095	34	8.4
Essayons	65	2	14	None	2	MCR	4365	14	7.6
Essayons	65	2	14	Perpendicular	2	MCR	4531	14	6.8
Essayons	65	2	14	Parallel	2	MCR	4531	14	7.3
Essayons	230	2	14	None	1	MCR	17	1	4.4
Essayons	230	2	14	Perpendicular	1	MCR	17	1	4.4
Essayons	230	2	14	Parallel	1	MCR	17	1	4.2
Essayons	280	2	14	None	1	MCR	6	1	3.9
Essayons	280	2	14	Perpendicular	1	MCR	6	1	3.9
Essayons	280	2	14	Parallel	1	MCR	6	1	3.9

Table 4. (contd)

STFATE Modeled Scenarios, Input Conditions							Maximum Value for Scenario		
Vessel	**Depth (ft)**	**Speed (kn)**	**Discharge Duration (min)**	**Bottom Slope Condition**	**Current (ft/sec)**	**Sediment Type**	**Vertical Impact Pressure (Pa)**	**Horizontal Shear Stress (Pa)**	**Mound Thickness (cm)**
Sugar Island	45	7	3	None	2	MCR	54327	73	10.8
Sugar Island	45	7	3	Perpendicular	2	MCR	55669	74	10.0
Sugar Island	45	7	3	Parallel	2	MCR	55669	74	9.9
Sugar Island	65	7	3	None	2	MCR	24311	52	8.2
Sugar Island	65	7	3	Perpendicular	2	MCR	24944	53	7.9
Sugar Island	65	7	3	Parallel	2	MCR	24944	53	7.8
Sugar Island	230	7	3	None	1	MCR	639	7	2.7
Sugar Island	230	7	3	Perpendicular	1	MCR	642	7	2.6
Sugar Island	230	7	3	Parallel	1	MCR	642	7	2.6
Sugar Island	280	7	3	None	1	MCR	363	5	2.3
Sugar Island	280	7	3	Perpendicular	1	MCR	340	5	2.2
Sugar Island	280	7	3	Parallel	1	MCR	365	5	2.3

Table 5. Predicted Maximum Values of Impact Pressure, Horizontal Shear Stress, and Mound Thickness for Discharge Perpendicular to Slope

Vessel Name	Water Depth (ft)	Discharge Duration (min)	Vertical Impact Pressure (Pa)	Horizontal Shear Stress (Pa)	Mound Thickness (cm)	Expected Bottom Velocity[a] (m/s)
Essayons	45	9	37,611	42.77	11.9	3.32
Essayons	65	9	7,427	18.87	9.3	2.40
Essayons	230	9	36	1.15	6.1	0.79
Essayons	280	9	13	0.59	5.3	0.72
Essayons	45	14	22,095	34.08	8.4	3.03
Essayons	65	14	4,531	13.80	6.8	2.12
Essayons	230	14	17	0.89	4.4	0.73
Essayons	280	14	6	0.59	3.9	0.65
Sugar Island	45	3	55,669	73.80	10.0	4.13
Sugar Island	65	3	24,944	52.66	7.9	3.61
Sugar Island	230	3	642	6.90	2.6	1.61
Sugar Island	280	3	340	4.96	2.2	1.41
a. Expected bottom velocity was determined using Miller, et al. (1977).						

Table 6. Bottom Current Velocity Predicted to Mobilize Bed Sediments

Estimated Velocity[a] Required To Mobilize Bed Sediment (m/s)	Bed Sediment Particle Diameter (mm)	Sediment Size Class
1.8	10	Medium gravel
2.5	20	Coarse gravel
3.4	40	Very coarse gravel
a. Estimated for spherical quartz grains using Miller et al. 1977.		
Note that bed sediments can be mobilized but depth of bed that will move is not known.		

Table 7. Estimated Near-Bottom, Wave-Generated Currents for Average Summer, Average Winter, 50-year, and 100-year Wave Conditions Near the Mouth of the Columbia River

Disposal Site Depth (ft)	Range of Bottom Current Velocities Estimated from Modeled Shear Stress (m/s)	Estimated Wave-Generated Bottom Current Velocity (m/s)[a]					
		Average Summer Wave Height H_s=4.9 ft (1.5 m), Wave Period T=8 s	Average Winter Wave Height H_s=9.8 ft (3 m), Wave Period T=12 s	50-year Wave Height H_s=32.8 ft (10 m), Wave Period T=12 s	100-year Wave Height H_s=40.7 ft (12.4 m), Wave Period T=12 s	50-year Wave Height H_s=32.8 ft (10 m), Wave Period T=15 s	100-year Wave Height H_s=40.7 ft (12.4 m), Wave Period T=15 s
45	3.03 – 4.13	0.45	1.10	3.65	4.04 (breaking)	4.15	4.26 (breaking)
65	2.12 – 3.61	0.31	0.86	2.70	3.35	3.11	3.86
230	0.73 – 1.61	nil	0.21	0.67	0.83	1.00	1.23
280	0.65 – 1.41	nil	0.14	0.46	0.56	0.78	0.97

a. Estimated using linear wave theory (Sherwood 2005).

7.0 References

Airriess, CN and BR McMahon. 1994. "Cardiovascular adaptations enhance tolerance of environmental hypoxia in the crab *Cancer magister.*" *Jour. Experimental Biology*, 190:23-41.

Antrim, LD and BD Gruendell. 1998. *Effects of Sand Accumulation on Juvenile Flatfish and Soft-shelled Dungeness Crab.* PNNL-1202. Prepared by the Battelle Marine Sciences Laboratory, Sequim, Washington, for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon. 22 pp.

Armstrong, DA; KA McGraw, PA Dinnel, RM Thom, and O Iribarne. 1987. *Model of Dredging Impact on Dungeness Crab in Grays Harbor, Washington*. Fisheries Research Institute, University of Washington, School of Fisheries; FRI-UW-8702.

Armstrong, DA; KA McGraw; PA Dinnel, RM Thom, and O Iribarne. 1991. *Construction Dredging Impacts on Dungeness Crab, Cancer magister, in Grays Harbor, Washington and Mitigation of Losses by Development of Intertidal Shell Habitat*. Fisheries Research Institute, University of Washington, School of Fisheries; FRI-UW-9110.

Armstrong, DA, C Rooper, and D Gunderson. 2003. "Estuarine production of juvenile Dungeness crab (*Cancer magister*) and contribution to the Oregon-Washington Coast Fishery." *Estuaries* 48:1174-1188.

Bratos, SM, BH Johnson, and JE Clausner. 2002. "Palos Verdes shelf pilot capping: Dredged material fate modeling for cap placement." In: *Proceedings, 21st Annual Meeting of the Western Dredging Association and 33th Annual Texas Dredging Seminar*. Houston, Texas.

Chang, BD and CD Levings. 1978. "Effects of burial on the heart cockle and the Dungeness crab." *Est. Coast. Mar. Sci*., 7:409-412.

Germano, JD and D Cary. 2005. "Rates and effects of sedimentation in the context of dredging and dredged material placement." DOER Technical Notes Collection (ERDC TN-DOER-E19), U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. 12 pp.

Hicks, D and BA Johnson. 1991. *A device to measure shell hardness of Dungeness crabs*. Prof. Paper 001. Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau, Alaska.

Hicks, D and BA Johnson. 1999. "A device to measure shell hardness of Dungeness crabs and trial application in the Kodiak Island, Alaska, commercial fishery." *Nor. Amer. J. Fish. Man.*19:581-590.

Kaminsky, GM, P Ruggiero, and G Gelfenbaum. 2000. "Monitoring Coastal Change in Southwest Washington and Northwest Oregon during the 1997/98 El Niño," *Shore and Beach*, July, pop.42-51.

Kruse, GH, D Hicks, and MC Murphy. 1994. "Handling increases mortality of softshell Dungeness crabs returned to the sea." *Alaska Fishery Research Bulletin* 1(1):1-9.

MacKay, DCG. 1942. "The Pacific edible crab, *Cancer magister*." *Bulletin of Fisheries Research Board of Canada* LXII:1-32.

Martinez, MM. 2001. "Running in the surf: hydrodynamics of the shore crab *Grapsus tenuicrustatus.*" *Jour. Experimental Biology* 204:2097-2112.

Maurer, D, RT Keck, JC Tinsman, and WA Leathem. 1980. "Vertical migration and mortality of benthos in dredged material – Part I: Mollusca." *Marine Environmental Research* 4:299-319

Maurer, D, RT Keck, JC Tinsman, and WA Leathem. 1981. "Vertical migration and mortality of benthos in dredged material – Part II: Crustacea." *Marine Environmental Research* 5:301-317.

Maurer, D, RT Keck, JC Tinsman, and WA Leathem. 1982. "Vertical migration and mortality of benthos in dredged material – Part III: Polychaeta." *Marine Environmental Research* 6:49-68

Maurer, D, RT Keck, JC Tinsman, WA Leathem, C Wenthe, C Lord, and TM Church. 1986. "Vertical migration and mortality of benthos in dredged material – A Synthesis." *Int. Revue ges. Hydrobiol.* 76(1):49-63.

McDowell, S., S. Pace, and D. Fischman. 2002. "Palos Verdes shelf pilot capping: Monitoring of hopper dredge operations during placement of cap material. In: *Proceedings, 21st Annual Meeting of the Western Dredging Association and 33th Annual Texas Dredging Seminar*. Houston, Texas.

McGaw, IJ. 2004. "Ventilatory and cardiovascular modulation associated with burying behaviour in two sympatric crab species, *Cancer magister* and *Cancer productus*." *Jour. Experimental Marine Biology and Ecology* 303:47-63.

McGaw, IJ. 2005. "Burying behaviour of two sympatric crab species: *Cancer magister* and *Cancer productus*." *Sci. Mar*. 69(3):375-381.

Miller, MC, IN McCave, and PD Komar. 1977. "Threshold of sediment motion under unidirectional currents." *Sedimentology* 24:507–527.

Moritz, HP, and HR Moritz. 2002. *Regional analysis of extremal wave height variability, Oregon Coast, USA.* U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Morton, JW. 1976. "Ecological Impacts of Dredging and Dredge Spoil Disposal: A Literature Review." Master's Thesis, Cornell University, Ithaca, New York, 112 pp.

Pearson, WH. 1987. *Conclusions of the Third Meeting of the Crab Study Panel Examining Issues Related to Dungeness Crab for the Grays Harbor Navigation Improvement Project.* PNL-6257. Prepared for the U.S. Army Corps of Engineers, Seattle District, by Battelle/Marine Sciences Laboratory, Sequim, Washington.

Pearson, WH, and DL Woodruff. 1987. *Effects of Proposed Dredged Materials from Grays Harbor on Bait Odor Response in Dungeness Crab (Cancer magister)*. PNL-6436. Prepared for the U.S. Army Corps of Engineers, Seattle District, by Battelle/Marine Sciences Laboratory, Sequim, Washington. Published by Pacific Northwest Laboratory, Richland, Washington.

Pearson, WH, DL Woodruff, P Wilkinson, JS Young, HL McCartney, and DC Klopfer. 1987. *Data Report for the 1984-1985 Ocean Surveys to Investigate Potential Ocean Disposal Sites off Grays Harbor, Washington*. PNL-6280. Prepared for the U.S. Army Corps of Engineers, Seattle District, by Battelle/Marine Sciences Laboratory, Sequim, Washington. Published by Pacific Northwest Laboratory, Richland, Washington.

Pearson, WH, GD Williams, and JR Skalski. 2002. *Estimated Entrainment of Dungeness Crab During Dredging for the Columbia River Channel Improvement Project*. PNNL-14129. Prepared for the U.S. Army Corps of Engineers, Portland District, by Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington.

Pearson, WH, GD Williams, and JR Skalski. 2003. *Estimated Entrainment of Dungeness Crabs During Maintenance Dredging of the Mouth of the Columbia River, Summer 2002*. PNNL-14190. Prepared for the U.S. Army Corps of Engineers, Portland District, by Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington.

Pearson, WH, GD Williams, and JR Skalski. 2005. *Dungeness Crab Dredging-Entrainment Studies in the Lower Columbia River, 2002-2004: Loss Projections, Salinity Model, and Scenario Analysis.* PNNL-15021. Prepared for the U.S. Army Corps of Engineers, Portland District, by Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington.

Roberts, RD, MR Gregory, and BA Foster. 1998. "Developing and efficient macrofauna monitoring index from an impact study- a dredge spoil example." *Marine Pollution Bulletin* 36(3):231-235.

Ruggiero, P, GM Kaminsky, PD Komar, and WG McDougal. 1997. "Extreme waves and coastal erosion in the Pacific Northwest." *Ocean Wave Measurement and Analysis, Proceedings of the 3rd International Symposium, Waves '97.* pp. 947-961.

Smith, SDA, and MJ Rule. 2001. "The effects of dredge-spoil dumping on a shallow water soft-sediment community in the Solitary Islands Marine Park, NSW, Australia." *Marine Pollution Bulletin* 42(11):1040-1048.

Taylor, JRA, and WM Kier. 2003. "Switching skeletons: Hydrostatic support in molting crabs." *Science* 301:209-210.

Smith, SDA, and MJ Rule. 2001. "The effects of dredge-spoil dumping on a shallow water soft-sediment community in the Solitary Islands Marine Park, NSW, Australia." *Marine Pollution Bulletin* 42(11):1040-1048.

U.S. Army Corps of Engineers. 1999. *Integrated Feasibility Report for Channel Improvements and Environmental Impact Statement Columbia and Lower Willamette River Federal Navigation Channel*. Published by the U.S. Army Corps of Engineers, Portland District. , August, 1999.

Wainwright, SA, WD Biggs, JD Currey, and JM Goslin. 1976. *Mechanical design in organisms*. John Wiley & Sons, New York.

Williams GD, WH Pearson, NR Evans, and MG Anderson. 2004. *Benson Beach Demonstration Project: Composition and Abundance of Biota at Three Alternative Sump Sites.* PNNL-14522. Prepared for the U.S. Army Corps of Engineers, Portland District, by Pacific Northwest National Laboratory, Marine Sciences Laboratory, Sequim, Washington.

Distribution

No. of
Copies

OFFSITE

6 K.W. Larson
U. S. Army Corps of Engineers
Portland District
Environmental Resources CENWP-PE-E
P. O. Box 2946
Portland, OR 97208-2946

1 J.R. Skalski
University of Washington
Fisheries Department
1325 4th Ave., Suite 1820
Box 358218
Seattle, WA 98101-2509

1 G.D. Williams
71 Libby Street
Sequim, WA 98382

No. of
Copies

ONSITE

4 Pacific Northwest National Laboratory

W.H. Pearson	SEQUIM
M.C. Miller	SEQUIM
N.P. Kohn	SEQUIM
Information Release	K1-06