
EXHIBIT K-4
EVALUATION REPORT
DUNGENESS CRABS
(REVISED)

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Exhibit K-4
Evaluation Report
Dungeness Crab (Revised)

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Evaluation Report Dungeness Crab

This report provides information regarding the impacts of dredging and disposal on Dungeness crab (*Cancer magister*) from construction of the Channel Improvement Project. Attached are two reports, one from Pacific International (PI) Engineering on the review and evaluation of the existing information on dredging and disposal impacts to Dungeness crabs in the Columbia River (Attachment A). The second is a final report from Pacific Northwest National Laboratory's (PNNL's) Marine Sciences Laboratory on the entrainment of crabs by dredging in the lower Columbia River (Attachment B). This study evaluated entrainment rates of Dungeness crab at the lower river shoals that would be expected to have crab. The entrainment rates are then used to calculate the loss of crabs to the population and fishery. It also includes information developed by PNNL on a preliminary salinity model to predict crab distribution and abundance based on salinity values. The information needs and study requirements were developed by a working group of Oregon and Washington State agencies, NOAA Fisheries, the Corps and the sponsor Ports. This group has reviewed the preliminary results of these studies and their comments were incorporated where appropriate. The results from these studies will be used to confirm projected impacts and schedule dredging to minimize impacts to crabs.

Direct measurements of crab entrainment rates were collected at three locations, in the lower Columbia River [Desdomona Shoals (CRM4.6-10), Upper Sands (CRM 13.6-17.5), and Miller Sands (21.4-25.2)] during the summer of 2002. These shoals spanned the range where Dungeness crab could occur in the project area. Entrainment rates for all age classes of crabs ranged from zero at Miller Sands to 0.224 crabs per cubic yard (cy) at Desdemona Shoals in June 2002. The overall average entrainment rate at Desdemona Shoals in September was 0.120 crabs per cy. A modified Dredge Impact Model (DIM) used the summer 2002 direct entrainment rates to project adult equivalent loss to the population and loss to the fishery for the Channel Improvement Project. Crab adult equivalent loss at age 2+ for project construction ranges from a worst case of 281,528 crabs to a best case of 38,811 crabs (of these amounts the increment associated with Channel Improvement is 166,888 crabs and 18,039 crabs). This translates to a loss to the fishery of between 44,342 and 7,252 crabs (the increment associated with Channel Improvement is 26,285 crabs and 3,347 crabs). This loss to the fishery compares to annual landings of 5.3 million crabs in the Washington and Oregon region around the Columbia River. To improve these projections, entrainment data from Flavel Bar is needed, since it represents a middle point in the distribution of crabs.

Crab losses from maintenance dredging for the 40-foot channel maintenance (no action alternative) and the 43-foot alternative maintenance (proposed project) were estimated for year one and year 20. Year one was selected because it was anticipated to have the largest dredging volume. Year 20 was selected because it represents a reasonable planning horizon for dredged material management planning. Additionally, 20 years represents a point in time beyond which dredging volumes will be considered constant. Projected adult equivalent loss in "no action" maintenance years 1 and 20 are 44,643 and 25,503 crabs, respectively. Projected loss to the fishery in "no action" maintenance years one and 20 are 7,031 and 4,017 crabs, respectively. Projected adult equivalent loss for maintenance of the 43-foot project (including quantities from the 40-foot as well as additional increment due to the 43-foot project) in years one and 20 are

56,840 and 25,612 crabs, respectively (the increment associated with channel improvement project is 12,197 crabs and 109 crabs). Projected loss to the fishery for maintenance of the project in years 1 and 20 are 8,953 and 4,035 crabs, respectively (the increment associated with channel improvement project is 1,922 crabs and 18 crabs). In other words, by maintenance year 20 or sooner, entrainment associated with the channel improvement project is effectively equal to that of the No Action Alternative.

The literature, analyses of salinity intrusion scenarios, and the summer 2002 site-specific data on entrainment and salinity, all indicate that bottom salinity influences crab distribution and entrainment, especially at lower salinity. It is now clear from field measurements of entrainment rates and salinity during a period of low river flow (90-150 Kcfs) and high salinity intrusion that entrainment rates are zero where bottom salinity is less than 16 o/oo most of the time. Further, entrainment rates of 2+ and older crab fall with decreasing salinity in a clear and consistent manner. More elaboration of the crab distribution - salinity model, especially concerning salinity and the movements of 1+ crab, is needed to make final recommendations on dredge timing to minimize impacts. It is anticipated that additional entrainment data will be collected at Flavel Shoal as well as potentially the other shoals in the summer of 2003 depending on availability of funds.

Based on the Corps' earlier analysis in the Final Integrated Feasibility Report for channel improvements and Environmental Impact Statement (1999 Final IFR/EIS), the attached PI Engineering report, and the attached PNNL report, it is anticipated that this impact will not have any significant affect on population structure or dynamics. Other factors such as, ocean climate conditions and natural population cycles have a far greater effect on the crab population levels. The Corps will use the salinity-abundance model to schedule dredging and disposal to further avoid and minimize impacts to crab.

ATTACHMENT A



Report for the Final Supplemental Environmental Impact Statement

The Impacts of the Columbia River Channel Improvement Project Dredging and Disposal on Dungeness Crabs (*Cancer magister*)

1. Introduction

The U.S. Army Corps of Engineers (Corps) and six lower Columbia River ports (Portland, St. Helens, Longview, Kalama, Woodland and Vancouver) propose to deepen the authorized 40-foot deep channel to a depth of 43 feet. This action would result in the dredging (with a hopper or pipeline dredge) of sections along the navigation channel in the Columbia River from Columbia River Mile (CRM) 106.5 to CRM 3.0. The Corps analyzed the impacts of deepening in the Final Integrated Feasibility Report for channel improvements and Environmental Impact Statement (1999 Final IFR/EIS) for the Columbia and Lower Willamette Rivers Navigation Channel, Oregon and Washington (Corps 1999).

This report provides information regarding the impacts of dredging and disposal to Dungeness crabs (*Cancer magister*) that has been developed since the 1999 Final IFR/EIS (Corps 1999) and the Draft Supplemental Environmental Impact Statement (Draft SEIS) (Corps 2002) were released. Additional analyses and efforts were made based on methods discussed amongst a working group of State agencies, the Corps and the sponsor Ports. This report covers the progress made in analyzing data and assessing impacts to crabs. This report is to be accompanied by a final report from Pacific Northwest National Laboratory's (PNNL's) Marine Sciences Laboratory (Pearson et al. 2002), describing results from direct sampling of entrainment and the development of a salinity versus crab abundance model.

2. Background of Dredge Impacts Analyses

In order to analyze effects of dredging on crabs in the lower Columbia River, several separate, yet coordinated, efforts were made to understand the effects of entrainment on crab in the channel. This section of the report discusses briefly the analyses made that were described in detail in the Draft SEIS technical memorandum (Corps 2002). Because one particular method (the direct sampling in conjunction with the habitat-based approach) has proven to be most accurate thus far, it is the focus of

additional discussion in the new PNNL report (Pearson et al. 2002) that accompanies this report.

2.1 Dredge Impact Model Applied to Previously Collected Data

The first approach at understanding impacts to crabs involved using an existing model (the Dredge Impact Model, or DIM) to calculate crab entrainment and immediate loss resulting from dredging in the Columbia River navigation channel. The model (Wainwright et al. 1992) was applied to density data from previous studies in the Columbia River (McCabe et al. 1986) to predict the rates of entrainment and immediate loss due to dredging in five areas between CRM 6 and CRM 25 of Reach 7 (Reach 7 extends from CRM 3 to CRM 29). The DIM was specifically developed to measure the entrainment effects of dredging on Dungeness crab in Grays Harbor, Washington (Armstrong et al. 1987; Wainwright et al. 1992). It has been an effective tool for that area, and is utilized extensively by the Corps Seattle District. Specifically, Pacific International (PI) Engineering used the Wainwright et al. (1992) version of the DIM (rather than Armstrong et al. 1987) for this analysis, as this version has been adjusted for more recent data and it is the DIM currently used by the Corps Seattle District. Therefore, this version of the DIM was applied to data from Reach 7 of the Columbia River navigation channel in order to estimate crab entrainment and immediate loss (Please see the technical memorandum from the Draft SEIS for the results of this effort [Corps 2002]). However, because the Corps Portland District, PI Engineering and WDFW were concerned that the entrainment rates in the Grays Harbor DIM were not fully appropriate for the Columbia River, and that the density data previously collected in the channel (McCabe et al. 1986) were not collected in a manner that was compatible with the DIM, another method of determining effects to crabs was initiated.

Data from the demonstration project reported in the Draft SEIS has been superseded by the direct entrainment sampling reported in Section 2.2 below and the attached PNNL report (Attachment B).

2.2 Direct Entrainment Sampling

As a result of the uncertainties with using the DIM model with the early McCabe et al (1986) data, it was decided by the interagency group that direct measurements of entrainment with a more statistically rigorous design were needed to assess crab losses. PNNL's Marine Sciences Laboratory was contracted by the Corps to design a sampling schedule and to collect additional data on crab entrainment using the Corps dredge *Essayons*. Data were collected in June, September and October 2002 (after the release of the Draft SEIS and technical memoranda), and these data are now considered the most accurate. The PNNL report,

(Attachment B, discusses these data in regards to effects of dredging on crabs in the lower Columbia River.

3. Disposal

3.1 Introduction and Description

Construction of the entire Columbia River Channel Improvement Project entails disposal of 19 million cubic yards (mcy) of dredged material at a combination of upland, shoreline, and ecosystem restoration sites (14.5 mcy resulting from channel improvement and 4.5 mcy from Operations & Maintenance [O&M] dredging of the existing 40-ft channel). However, most of this material would not be disposed of in areas that are inhabited by Dungeness crab. One shoreline site and two ecosystem restoration sites within Reach 7 would be used for disposal, but they are all located above CRM 18 (see the Draft SEIS technical memorandum for more details on these areas [Corps 2002]). Based on the habitat information presented in the PNNL report (Pearson et al. 2002), disposal at these areas is not expected to contribute to crab loss.

Flowlane disposal associated with channel maintenance would occur between CRM 3 and CRM 18. The 43-ft project would add approximately 0.7 mcy to the 6.9 mcy of maintenance disposal expected from the 40-ft channel between CRM 3-5. There would also be approximately 0.1 mcy/yr of incremental maintenance material (2 mcy total over 20 years) from the 43-ft project disposed of between CRM 13-18. This would be in addition to the 1 mcy of maintenance material from the 40-ft channel expected during the 20-year project life. Since the flowlane disposal area between CRM 3-5 provides suitable crab habitat, it is likely that there will be some impact to individual crabs from this disposal. The flowlane disposal areas between CRM 13-18 provide no or only marginal crab habitat; therefore, disposal impacts to crabs at these sites are not expected.

The Corps' preferred option for ocean disposal involves no disposal of construction dredge material at the deep-water ocean disposal site (DWS), as well as no disposal of Incremental Maintenance (IM) dredge material at the DWS for the life of the project. Rather, the Corps would beneficially use the material for the creation of the ecosystem restoration sites instead of exclusively using the DWS. If the ecosystem restoration projects do not occur, then some material would be disposed of at the DWS. In this case, the maximum volume of construction material that would be placed at the DWS if it became necessary is 6 mcy. Subsequent maintenance dredging over the projected 20 years is predicted to yield approximately 6 mcy of dredged material, which may be disposed of at the DWS. No

dredged material generated by the project is planned for disposal at “Site E.”

A hopper dredge would be used for disposing dredged material to the flowlane disposal sites and if necessary to the DWS. It would also be used for conveying material to the sumps to be used in construction of the ecosystem restoration sites. Hydraulic pipeline would be used for creating the shoreline sites and other ecosystem restoration sites.

Disposal of dredged material at the flowlane disposal sites and the DWS from the Columbia River Channel Improvement Project has the potential to impact Dungeness crab and other biological resources by direct or indirect mechanisms. Potential impact mechanisms include burial, turbidity, dissolved oxygen (DO) reduction, and habitat alterations. Those mechanisms that are concluded to be pertinent for the Columbia River Channel Improvement Project were thoroughly evaluated relative to the potential for impacts at the DWS and general upriver areas that may support crabs in the 1999 Final IFR/EIS for this project (Corps 1999). Because the shoreline sites and ecosystem restoration sites are located upstream of significant crab distribution, no further discussion of crab losses related to these sites will be presented in this report. Only effects to the flowlane disposal sites and the DWS are discussed below.

3.2 Direct Impacts of Disposal

The loss of crabs at a disposal site is most likely related to the abundance of crabs, their level of activity, and the rate of delivery of the dredged material. Based on the information in the 1999 Final IFR/EIS (Corps 1999), crabs that cannot dig out of the material as it settles could suffer mortality. However, the deeper the water in which material is being disposed, the shallower the depth of material that would cover the bottom of the disposal site.

Crabs could be lost or injured during disposal within the flowlane due to burial; however, potential burial is likely only an issue at the one flowlane disposal site between CRM 3-5, as crabs are not expected to occur at the two sites between CRM 13-18. Although crabs would be buried by sediments during disposal, strong currents and flow within the flowlane may disperse the material and decrease the potential for death to the crabs due to burial.

The potential for losses of crab at the DWS, due to burial, is related to how the deposited material settles to the bottom. Based on the depth of the site, the barge would be located approximately 200-300 ft above the ocean floor. After release from the hopper, dredged material falls through the water column, convects/diffuses laterally, and eventually rests on the

seafloor. The disposal footprint depends upon vessel speed, water depth, currents, and ambient bathymetry. The currents, speed of the vessel, and the water depth would determine whether the material settles compactly or diffusely on the ocean bottom. A model based on typical mouth of the Columbia River (MCR) conditions estimated that the time required for sand to completely settle out of the water column is approximately 200 seconds (3.3 minutes) at the DWS (Corps 1999). Overall, the conditions at the DWS are very conducive to deposition of material over a relatively wide area, at a thin enough layer, and over a long enough period so that crabs of all size classes would have an opportunity to escape from the deposited material. The potential for burial and ultimately mortality of crabs at the DWS is considered fairly low.

Crab distribution and abundance data have recently been taken at the DWS as part of the baseline survey for the site. This information is still being analyzed, but some preliminary results are discussed in Section 5.

The total area potentially affected by flowlane and ocean disposal is very small relative to total available crab habitat in the Columbia River estuary and near shore ocean area.

4. Indirect Impacts of Dredging and Disposal

4.1 Introduction

Numerous physical attributes of and processes in the estuary and lower river have the potential to affect Dungeness crab. These include salinity, temperature, turbidity, suspended sediment, bathymetry and hydrodynamics. Changes in these physical attributes and processes can directly affect crab, and can also indirectly affect crab by affecting their habitat. Extensive analyses of the physical attributes and processes in the estuary and lower river have been conducted through the ESA consultation and NEPA/SEPA review for the channel improvement project. These analyses include the efforts of the independent SEI scientific review panel, as well as the substantial subsequent efforts of the consultation biological review team, consisting of biologists and other resource specialists from the Corps, NOAA Fisheries and the US Fish and Wildlife Service. Their efforts are reflected in the Project's Biological Assessment (January, 2002) and Biological Opinions (May, 2002).¹ In addition, the Corps built upon the analysis conducted through the consultation process as the foundation for the NEPA/SEPA review in the Project's Supplemental EIS.

¹ The rigorous reconsultation analyzed and resolved all of the concerns NMFS initially raised in August 2000 when it withdrew the first Biological Opinion, including those regarding the potential impact of project-related physical changes in the estuary on ecological conditions which Ecology had noted as a significant basis for denial of 401 certification (*see* "Reason One" in Ecology's 9/9/00 denial letter).

Much of the analysis in the early stages of the ESA consultation (i.e., the SEI scientific review process) was done with an eye toward effects on ESA-listed species (i.e., development of the ESA conceptual model).² Nevertheless, the resulting analysis of physical attributes and processes that was necessary input to the ESA conceptual model is directly relevant to an assessment of the project's potential effects on Dungeness crab because the same attributes and processes that have the potential to affect fish have the potential to affect crab. Accordingly, potential changes in salinity, temperature, turbidity, suspended sediment, bathymetry and hydrodynamics, which have all been identified as having the potential to affect crab, were all analyzed in the ESA consultation, as were other indicators relevant to crab such as nutrient and detrital transport and near shore habitat primary productivity. This analysis of effects on crab therefore directly benefits from the work that has been done to date for the ESA consultation and NEPA/SEPA review.

Potential effects on crab habitat include disturbance from dredging, disposal and ecosystem restoration activities. However, as discussed in Section 3.1, other than the estuarine flowlane disposal areas and the DWS, none of the disposal or ecosystem restoration areas are significantly inhabited (if at all) by Dungeness crab (i.e., the areas downstream of CRM 18). Accordingly, the only potential direct effects to crab habitat are from dredging the channel in the estuary, and from use of the estuarine flowlane disposal areas (located between CRM 3 and 18) and the DWS, which is not expected to be used at all if the ecosystem restoration features are constructed. Indirect effects on Dungeness crab resulting from both dredging and disposal are described below in Sections 4.2 and 4.3.

4.2 Indirect Effects of Dredging

² As discussed above, much of the conceptual model developed for the reconsultation process is relevant for understanding potential impacts to non-ESA listed species and their habitat. For example, the model's links between physical/chemical indicators and many biological indicators provide information regarding basic ecosystem functions that are relevant to listed and non-listed species alike. As Table S6-1 of the SEIS indicates, the model provides basic information regarding:

- Habitat-forming Processes (suspended sediment, bedload, woody debris, turbidity, salinity, accretion/erosion, bathymetry);
- Habitat Types (tidal marsh and swamp, shallow water and flats, water column);
- Habitat Primary Productivity (light, nutrients, imported and resident phytoplankton production, benthic algae production, tidal marsh and swamp production); and
- Food Web (deposit feeders, mobile macroinvertebrates, insects, suspension/deposit feeders, tidal marsh macrodetritus, resident microdetritus).

For example, if someone was interested in understanding the project's effects on tidal marsh and swamp, they could use the portion of the model that addresses habitat types. Similarly, a question regarding deposit feeders, mobile macroinvertebrates or insects could be answered by reviewing the model's discussion of those indicators. Because the model was developed to review impacts to salmon, there may be some components of the ecosystem that the model does not address; however, the model provides the best available information regarding the lower Columbia River ecosystem and potential effects of the project.

Dredging would disturb the riverbed within the channel, and increase its depth by 3 feet. The channel of the Columbia River is quite dynamic compared to habitats on the margins of the River that are characterized by higher deposition rates and finer substrate. Long-period sand waves occur on the riverbed in the navigation channel, and they migrate downstream as sand is transported by the river flow. This migration of material downstream yields a benthic environment that is constantly disturbed by natural processes. A short-term change in the characteristics of the benthic communities can be expected in dredged areas in the estuary; however, these organisms are expected to recolonize the dredged areas and the habitat is expected to recover quickly (Richardson et al. 1977, Van Dolah et al. 1984 and McCabe et al. 1996, as cited in Nightingale and Simenstad 2001; also see Sections 6.1.17, 6.1.20 and 6.2.4 of Biological Assessment). In addition, sand waves are expected to re-form within dredged areas of the channel shortly after construction of the improvement project (within a period of weeks to months), thereby quickly returning the substrate (i.e., grain size, sorting and compaction) of channel-area habitat to pre-construction conditions. Accordingly, any indirect effect to crab from this immediate riverbed disturbance should be minimal. Such effects would also be similar to the effects from annual O&M dredging (the No Action Alternative).

Other potential indirect effects on crab habitat include potential ecosystem changes resulting from any anticipated changes in turbidity, suspended sediment, turbidity, salinity, temperature, bathymetry and hydrodynamics. Such effects on crab habitat, if any, are expected to be minimal because the analysis of the projected changes to these physical parameters shows minimal if any change as a result of channel improvement. The analysis of these physical indicators is summarized in Table 1, which provides citations to the relevant sections of the Biological Assessment and the Supplemental EIS.

*Columbia River Channel Improvement Project
Final Supplemental Integrated Feasibility Report and Environmental Impact Statement*

INDICATOR / PHYSICAL ATTRIBUTE OR PROCESS	HISTORIC AND EXISTING CONDITIONS (BA Sections)	ANTICIPATED EFFECT FROM CHANNEL IMPROVEMENT (BA & SEIS Sections)	SUMMARY
SUSPENDED SEDIMENT	2.2.1.1 2.3.1.1	6.1.1 (BA) 6.2.2.1 (SEIS)	<ul style="list-style-type: none"> • Suspended sediment transport historically had high natural variability • Flow regulation has reduced variability somewhat and has reduced annual transport • Concentration is a function of flow rate and also has high variability • Project is not expected to change volume or rate of suspended sediment transport • Some temporary increases to suspended sediment concentration may occur in vicinity of dredging and disposal activities • Temporary increases are generally small compared to background levels and are all well within range of natural variability
TURBIDITY / TURBIDITY MAXIMUM	2.2.1.4 2.3.1.4	6.1.4 (BA) 6.3 (SEIS)	<ul style="list-style-type: none"> • Like suspended sediment, turbidity levels vary with flow levels and have relatively high level of natural variability • Similarly, flow regulation has reduced natural variability in turbidity • Estuarine Turbidity Maximum (ETM) has been observed in both north and south channels • ETMs shift up to 9 miles each day with tides and river discharge, and have been observed between River Miles (CRM) 5 and 20 • Project is not expected to result in observable increases in turbidity in areas where neither dredging nor disposal is occurring • In areas where dredging and disposal are occurring, temporary localized increases in turbidity are expected to occur • Temporary localized increases are generally small and are not likely to produce detectable effects on plant growth • Project may result in some upstream shift in ETMs (up to 1 mile) due to changes in salinity intrusion, but anticipated shift is much less than daily fluctuation caused by tidal cycle
SALINITY	2.2.1.5 2.3.1.5	6.1.5 (BA) 6.2.2.3 (SEIS)	<ul style="list-style-type: none"> • Salinity intrusion into estuary varies with channel depth, strength of tides and river flows • Salinity intrusion likely had high historic seasonal variability given higher historic variability in flows • Seasonal variability has likely been reduced by flow regulation

			<ul style="list-style-type: none"> • Salinity intrusion is driven by tidal forcing processes that also drive location of ETM • Modeling results predict minor increases in salinity due to deepening navigation channel (up to 0.5 ppt in shallow embayments, and up to 5 ppt in the channel itself) • Predicted embayment changes are much smaller than natural temporal variations due to normal variations in freshwater flow and tidal dynamics
TEMPERATURE	2.2.6.5 2.3.6.5	6.1.35 (BA) 6.3 (SEIS)	<ul style="list-style-type: none"> • River temperature varies depending on flow, season and climate conditions • Historic temperatures in the mainstem in the estuary were likely cooler than today due to numerous factors, including: slowed river flow, reduced riparian canopy, agricultural runoff, and industrial discharges • Primary factor potentially affecting temperature in the estuary after project construction would be increased intrusion of cooler ocean water, which would result in reducing, rather than increasing temperatures in the estuary • However, given the negligible projected change in salinity after construction, a change in temperature is not anticipated
BATHYMETRY / HYDRO- DYNAMICS	2.2.1.7 2.2.5.2 2.3.1.7 2.3.5.2	6.1.7 6.1.26 (BA) 6.2.2.1 6.2.2.2 6.2.2.4 (SEIS)	<ul style="list-style-type: none"> • Flow regulation has reduced the overall flow volume and velocity as well as historic natural variability in velocities • No dredging (and therefore no change in bathymetry) proposed for approximately 55% of the channel in the estuary • Models predict insignificant changes in velocity from deepening (from -0.2 to 0.2 ft/sec in the channel and from -0.05 to 0.05 ft/sec in the shallow regions outside the channel), which are much smaller than natural variation • Models also predict minimal changes in surface water elevation from deepening (from -0.02 to +0.02 foot in the estuary), again, much lower than natural variation • Slight predicted changes in river hydraulics/hydrodynamics are too small to affect sand transport or accretion/erosion in the estuary
NUTRIENT / DETRITAL TRANSPORT & NEARSHORE HABITAT PRIMARY PRODUCTIVITY	2.2.3 2.3.3	6.1.5.2 6.1.11 – 6.1.16 (BA) 6.7.1.1 (SEIS)	<ul style="list-style-type: none"> • Relative to historic conditions, primary productivity in the estuary has shifted from a marsh-based macrodetrital food web to a microdetrital food web • The effect of potential shift in location of ETM after construction on distribution of nutrients in the estuary is expected to be immeasurably small • No changes to primary productivity are anticipated as a result of the project

4.3 Indirect Effects of Disposal

Disposal in the flowlane areas would disturb the riverbed habitat within the channel. As with disturbances to the benthic environment caused by dredging (Section 4.2), the riverbed and the benthic organisms present there are expected to recover from the disturbance of disposal relatively quickly (Richardson et al. 1977, Van Dolah et al. 1984 and McCabe et al. 1996, as cited in Nightingale and Simenstad 2001; also see Sections 6.1.17, 6.1.20 and 6.2.4 of Biological Assessment). Any potential impact to crab habitat resulting from these disturbances is expected to be limited to the flowlane disposal area likely inhabited by crab at CRM 3-5. Furthermore, similar impacts currently occur from annual flowlane disposal (the No Action Alternative). Therefore, any indirect effect to habitat is expected to be minimal.

The benthic habitat at the DWS is not subjected to high wave and current action. This results in a fine-grained substrate and a stable environment as compared to inshore environments. The stability of the area likely promotes a higher diversity of benthic species with greater densities as compared to the inshore benthic community (Corps 1999). The inshore community, adapted to a higher-energy environment, generally comprises colonizing species, tube dwellers, and rapid burrowers. Both communities tend to show high inter- and intra-annual variability in community structure (Corps 1999).

Disposal of dredged material at the DWS would yield a small increase in the mean grain size of the substrate, which may lead to changes in the benthic community. However, after ocean disposal in June 1989, Hinton et al. (1992, as cited in Nightingale and Simenstad 2001) found there to be an increase in benthos densities when measured in June 1990. Although a slight decrease in productivity was assumed to be probable during disposal and shortly after, successful recolonization had occurred by June 1990. Therefore, the habitat alteration is expected to have essentially no adverse impact on crab populations in the area because the deposited material falls within the range of material that is suitable for this species and the prey they consume.

5. Assessment of Impact

Overall, dredging would occur in areas where the adult equivalent loss to the crab population and loss to the fishery is expected to be low (based on the 2002 studies). The results of the 2002 studies and further elaboration of the crab-salinity model will be used to evaluate and schedule dredging to minimize impacts to crabs.

An analysis of anticipated changes, if any, in physical attributes and processes in the estuary and lower river indicates that the channel

improvement project's indirect effects on Dungeness crab (i.e., its effects on crab habitat and prey) will be minimal. Information on individual physical indicators is summarized in Table 1. A more complete presentation of this information can be found in the sections of the Biological Assessment and Supplemental EIS noted in the table.

The volume of disposal material from construction would be placed in areas that have no or few crabs. No material will be disposed in the DWS if the ecosystem restoration sites are used for disposal of material (as preferred).

The Corps' plan for addressing crab impacts has been to focus on avoiding impacts to crab through site selection. The DWS was selected following a detailed screening process. The Corps has been able to further avoid potential impacts that could have occurred at the DWS under its preferred alternative, which beneficially uses sand that originally would have gone to the DWS during construction for ecosystem restoration projects added during consultation under the Endangered Species Act (ESA). This change to the Project reduces the volume of disposal at the DWS from 6.2 to 0 mcu of construction material, and eliminates disposal of O&M material to the DWS.

MEC Analytical Services, under contract to the Corps, has further investigated the distribution and abundance of crabs and benthic organisms at the DWS. The study began in summer 2002; the data are currently being analyzed, and will likely be reported in spring 2003. Preliminary results indicate that there were more crabs found at the DWS in late summer than in early summer, by an approximate factor of 10. Additionally, the crabs were larger and softer in late summer than they were in early summer. The final results from this study will be used to verify the conclusions of this report with regard to the potential for impacts to crab due to disposal of dredged material at the DWS. Further, such data will serve as a basis for considering measures to minimize impacts to crabs in the event that the study yields conclusions of high crab populations seasonally.

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ESTIMATED ENTRAINMENT OF DUNGENESS CRAB DURING DREDGING FOR THE COLUMBIA RIVER CHANNEL IMPROVEMENT PROJECT

W. H. Pearson
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January 2003

Prepared for Portland District
U.S. Army Corps of Engineers
Portland, Oregon

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ESTIMATED ENTRAINMENT OF DUNGENESS CRAB DURING DREDGING FOR THE COLUMBIA RIVER CHANNEL IMPROVEMENT PROJECT

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ABSTRACT

The studies reported here focus on issues regarding the entrainment of Dungeness crab related to the proposed Columbia River Channel Improvement Project and provide direct measurements of crab entrainment rates at three locations (Desdemona Shoals, Upper Sands, and Miller Sands) from RM4 to RM24 during summer 2002. Entrainment rates of all crab age classes ranged from zero at Miller Sands to 0.224 crabs per cy at Desdemona Shoals in June 2002. The overall entrainment rate at Desdemona Shoals in September was 0.120 crabs per cy. A modified Dredge Impact Model used the summer 2002 entrainment rates to project crab entrainment, adult equivalent loss, and loss to the fishery for the Channel Improvement Project. For construction dredging, estimates of overall adult equivalent loss at age 2+ range from 38,811 to 281,528 crabs. Also for construction dredging, overall losses to the fishery range from 7,252 to 44,342 crabs. For annual maintenance dredging under the Proposed Plan (43' Channel), estimates of adult equivalent loss at age 2+ range from 56,840 crabs in Year 1 to 25,612 crabs in Year 20. Also for maintenance dredging under the Proposed Plan, estimated losses to the fishery range from 8,953 to 4,035 crabs in Year 1 and 20, respectively. The worst-case projected fishery losses represent approximately 1% of the annual crab landings for the Washington and Oregon region around the Columbia River (5.3 million crabs from 1991 to 2001). To improve the projections, entrainment data from Flavel Bar and Tongue Point are needed. Similarly, additional sampling days at each upriver location would narrow confidence limits associated with entrainment projections. The literature, analyses of salinity intrusion scenarios, and the summer 2002 site-specific data on entrainment and salinity all indicate that bottom salinity influences crab distribution and entrainment, especially at lower salinities. It is now clear from field measurements of salinity during a period of low river flow (90-150 Kcfs) and high salinity intrusion that entrainment rates are zero where bottom salinity is less than 16 o/oo most of the time. Further, entrainment rates of age 2+ and older crab decline in a clear and consistent manner as salinity decreases. More elaboration of the crab distribution- salinity model is needed, especially concerning salinity and the movements of age 1+ crab.

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EXECUTIVE SUMMARY

Proposed dredging during the Columbia River Channel Improvement Project has raised concerns about dredging-related impacts on Dungeness crab in the Columbia River Estuary. The Portland District of the U.S. Army Corps of Engineers engaged the Marine Sciences Laboratory of the U.S. Department of Energy's Pacific Northwest National Laboratory to review the state of knowledge and conduct studies concerning dredging-related impacts from entrainment on Dungeness crab from the Columbia River Channel Improvement Project. The studies accomplished three tasks regarding the entrainment of Dungeness crab related to the proposed Channel Improvement Project. The first task provided direct measurements of crab entrainment rates at three locations (Desdemona Shoals, Upper Sands, and Miller Sands) from RM4 to RM24 during summer 2002. The second task used the summer 2002 entrainment data and a modified Dredge Impact Model to project crab entrainment, adult equivalent loss, and loss to the fishery from planned dredging. The third assessed the influence of salinity on crab distribution and entrainment.

Entrainment rates for all age classes of crabs ranged from zero at Miller Sands to 0.224 crabs per cy at Desdemona Shoals in June 2002. The overall entrainment rate at Desdemona Shoals in September was 0.120 crabs per cy.

A modified Dredge Impact Model used the summer 2002 entrainment rates to project crab entrainment, adult equivalent loss, AEL and loss to the fishery associated with construction and maintenance dredging. For construction dredging, estimates of overall AEL at 2+ range from 38,811 to 281,528 crabs. Also for construction dredging, overall losses to the fishery range from 7,252 to 44,342 crabs. For annual maintenance dredging under the Proposed Plan (43' Channel), estimates of adult equivalent loss at age 2+ range from 56,840 crabs in Year 1 to 25,612 crabs in Year 20. Also for maintenance dredging under the Proposed Plan, estimated losses to the fishery range from 8,953 to 4,035 crabs in Year 1 and 20, respectively. The worst-case projected fishery losses represent approximately 1% of the annual crab landings for the Washington and Oregon region around the Columbia River (5.3 million crabs from 1991 to 2001). To improve the projections, entrainment data from Flavel Bar and Tongue Point are needed. Additional sampling days at each upriver location would also narrow confidence limits associated with entrainment projections.

The scientific literature, analyses of salinity intrusion scenarios, and the summer 2002 site-specific data on entrainment and salinity all indicate that bottom salinity influences crab distribution and entrainment, especially at lower salinities. It is now clear from field measurements of entrainment rates and salinity during a period of low river flow (90-150 Kcfs) and high salinity intrusion that entrainment rates are zero where bottom salinity is less than 16 o/oo most of the time. Further, entrainment rates for 2+ and older crab decline in a clear and consistent manner as salinity decreases. More elaboration of the crab distribution- salinity model is needed, especially concerning salinity and the movements of 1+ crab.

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1.0 INTRODUCTION

Proposed dredging of the Columbia River has raised concerns about dredging-related impacts on Dungeness crab in the Columbia River Estuary (CRE). The Portland District of the 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 and conduct studies concerning dredging-related impacts from entrainment on Dungeness crab from the Columbia River Channel Improvement Project. Previously, MSL performed crab studies for the Corps Seattle District during that district's Grays Harbor Navigation Improvement Project (e.g., Pearson 1987, Pearson and Woodruff 1987, Pearson et al. 1987). This document focuses on issues regarding the entrainment of Dungeness crab related to the proposed Columbia River Channel Improvement Project and presents results of field studies conducted from River Mile 3 (RM3) to RM24. A separate report will describe field studies of crab entrainment during 2002 dredging at the Mouth of the Columbia River (MCR).

This document first presents a general background on Dungeness crab biology, the influence of salinity on crab distribution, and the use of a modified Dredge Impact Model (DIM) to estimate entrainment impacts to Dungeness crab for the Columbia River Channel Improvement Project. The document then presents the methods and results from three tasks. The first task was to conduct field studies during the spring and summer of 2002 aboard the Corps' Dredge *Essayons* to measure crab entrainment rates in some of the areas to be dredged during the proposed project. The second task was to use the 2002 data to estimate crab entrainment impacts for the dredging planned for the Channel Improvement Project. The third task was to postulate scenarios of different salinity regimes and assess their potential influence on crab distribution. The document concludes with a discussion of the results of the three tasks.

1.1 Biology of Dungeness Crab

Dungeness crabs use both the nearshore ocean environment and the estuary in their life cycle (Tasto 1983, Armstrong et al. 1987, Rooper et al. 2002). Adult female crabs extrude fertilized eggs in the fall and carry the extruded eggs until hatching in the ocean in late winter. After a 4 to 5 month larval period, the megalopae, the last larval stage, settle to the bottom to become the first crab instar stage (Young of the Year or YOY). In the spring, large numbers of YOY enter the estuaries of the West Coast as late megalopae and perhaps as first true crab. YOY (age 0+) crabs in the estuary grow faster than those in the ocean. Juvenile crabs (age 1+) found in the estuary derive either from 0+ crabs that over-wintered in the estuary or from 1+ crabs entering the estuary in the summer. To gain perspective, an understanding of the ways in which Dungeness crab use the estuary and how that use may or may not expose them to dredging activity is needed. In spring and summer, 0+ crabs can be found in the Mouth of the Columbia River (MCR) with annual average densities varying over two orders of magnitude from year to year (Larson 1993). In the Columbia River, Dungeness crabs are found from the MCR to about RM17 (McCabe et al. 1986, 1989).

It is clear that Dungeness crabs use not only estuarine navigation channels but also other estuarine habitat areas. Age 0+ crabs are found in intertidal and shallow subtidal areas on substrates with shell hash, eelgrass, or other shelter (Armstrong et al. 1987). After growing to 20-mm carapace width (CW), the 0+ crabs move to subtidal areas. Age 1+ crabs use subtidal areas and forage over intertidal areas during high tide. A recent survey of four West Coast estuaries by Rooper et al. (2002) indicates that Dungeness crabs show consistent use of some estuarine habitat types. Side channel habitat near the estuary mouth has highest crab densities, with the lower estuarine main channel and upper estuary having significantly lower densities (Table 1). The characteristics of the preferred lower side channel habitat include shell, macroalgae, shallow depths, high food abundance, temperatures <18 degrees C, and salinities above 25 o/oo. The coastal estuaries are estimated to be the basis for 20% to 40% of West Coast Dungeness crab fishery production (Armstrong personal communication). The estuaries appear to provide relatively steady contributions to annual crab production while nearshore ocean environments provide crab production that is quite variable from year to year (Armstrong personal communication).

1.2 Salinity Influences on Crab Distribution

Salinity has long been suspected to influence the distribution and abundance of Dungeness crabs in west coast estuaries (Tasto 1983, Stevens and Armstrong 1984, McCabe et al. 1986). The notion that low salinity restricts crab distribution is supported by findings that Dungeness crabs are weak osmoregulators and become inactive under low salinity (McGaw et al. 1999). Dungeness crabs were previously thought not to survive at salinities less than 12 o/oo, but recent laboratory studies suggest the ability to survive brief exposure to low salinity. Dungeness crabs show adaptive physiological responses under 6 to 8 h exposures to 50% seawater (about 16 o/oo) (Brown and Terwillger 1992, 1999, McGaw and McMahan 1996, McGaw et al. 1999). Dungeness crabs can acclimate to continuous exposure to 50% seawater (about 16 o/oo) for 4 days (McGaw and Mahon 1996) and survive 24-h exposure to a salinity of 8 o/oo (McGaw et al. 1999).

Although Dungeness crab can survive brief exposure to low salinities, studies suggest that they do so by being inactive and isolating themselves. Dungeness crabs can detect a 4% decrease and 5% increase from ambient salinity (Sugarman et al. 1983) and exhibit behavioral responses to lowered salinity that serve to isolate the osmoregulatory organs from the changing salinity (Sugarman et al. 1983, McGaw et al. 1999). Sugarman et al. (1983) found that the threshold at which 50% of Dungeness crab close their mouthparts and seal the branchial chamber was 50% seawater (15.5 o/oo). McGaw et al. (1999) observed that under decreases to 75%, 50%, and 25% seawater (about 24, 16, and 8 o/oo), Dungeness crabs initially showed an immediate increase in movement that lasted less than one hour, after which time the crabs buried and became inactive. Crabs not only became inactive but also retracted the antennules and closed their mouthparts to seal the branchial chamber. At 25% seawater (8 o/oo), the antennules were retracted almost 100% of the time. When the antennules are retracted and the branchial chamber sealed,

the chemosensory abilities of Dungeness crabs to detect food and other chemical cues are substantially reduced.

Although previous field studies using linear models have found low correlations between crab density and salinity (Stevens and Armstrong 1984, McCabe et al. 1986), our examination of the data of Stevens and Armstrong (1984) using logarithmic models as well as linear models revealed that mean station density for 1+ and older crabs is logarithmically related to mean bottom salinity (Figure 1). The relationship between salinity and 0+ crab density appears to be more complex (Figure 1). Regression of logarithmically transformed data of Stevens and Armstrong (1984) for 1+ and older crab yields a significant regression equation ($p=0.004$) with an R-squared of 71% (Figure 2). This equation enables forecasting of crab density from salinity data. For example, predicted crab density at a bottom salinity of 16 o/oo is less than 1% of that at 32 o/oo (Figure 2). It is hypothesized that at bottom salinities above 30 o/oo crab density is governed by factors other than salinity and that as bottom salinity falls below 30 o/oo crab density falls logarithmically. Coupling the above salinity-crab density relationship with examination of the complex salinity regime in the Columbia River Estuary enables us to elaborate a conceptual model of the influence of salinity on crab distribution along the South Channel.

Salinity intrusion in the Columbia River is complex and dynamic compared to other estuaries. Two factors contribute to that complexity (Jay and Smith 1990). First, the Columbia River Estuary has extremely large freshwater flows moving through a shallow estuary. Second, the Columbia River Estuary has two channels. Tidal exchange dominates in the North Channel, which is saltier. River flow dominates in the South Channel, which is less salty. River flow levels and neap-spring tide transitions interact to produce the greatest salinity intrusion at neap tides during low flows (Table 2). The interaction of river flow and tidal exchange leads to general declines in bottom salinity at the South Channel as one moves upriver (Table 3). Bottom salinity at and above RM 10 shows substantial variation (Table 3).

Examination of the river flow records for 2001/2002 and the CORIE/ELCIRC models enables discernment of recent extremes in salinity intrusion. From October 2001 to October 2002, the combined river flow has varied from a low of 80 Kcfs on October 8 2001 to a high of 433 Kcfs on April 17 2002 (Figure 3). Predictions of the bottom salinity from the CORIE/ELCIRC Model (<http://www.ccalmr.ogi.edu/CORIE/>) also reveal that mean bottom salinity decreases moving upriver along the South Channel and that salinity intrusion varies with river flow (Figure 4). Using the CORIE/ELCIRC predictions for CORIE stations greater than 10 m deep in the South Channel indicates that mean bottom salinities at RM18 would be 10 o/oo for May 21 2002 with a river flow of 292 Kcfs and 23 o/oo for September 1 2002 with a river flow of 133 Kcfs.

1.3 Entrainment Measurements and Modeling

Armstrong and his colleagues (Armstrong et al. 1987, Wainwright et al. 1990, Wainwright et al. 1992) developed the Dredge Impact Model (DIM) for use in the Grays

Harbor Navigation Improvement Project of the Corps Seattle District. The model evolved over the years and Wainwright et al. (1992) gives a succinct overview of its present form. The DIM takes as inputs the volume of material to be dredged and the density of crab in the environment, applies an entrainment function plus age- and season-specific schedules of post-entrainment mortality and natural survival, and yields an estimate of loss to the crab fishery. The actual loss to the fishery is a function of harvest rate. The entrainment function, a key component of the model, was developed from several years of paired observations of the number of crab entrained per cubic yard (cy) dredged versus the crab density (crabs/hectare) determined by scientific trawling. For Grays Harbor, the model was successfully employed to minimize crab impacts through dredge scheduling and to estimate project impacts.

In reviewing the model for use in gaining perspective on crab impacts in the Columbia River, the model structure was found to be generally applicable but the entrainment function and the available data on crab density are not appropriate for use to estimate the effects of dredging on the Columbia River crab population and crab fishery. The entrainment function is probably site specific. The slope of entrainment function in Grays Harbor appears to differ substantially from what the available data from Columbia River indicate (Figure 5). Also, the relationship between crab density from trawls and crab density from dredge entrainment are not the same in Grays Harbor as in the Columbia River (Table 4). Therefore, it would not be appropriate to apply the entrainment function from Grays Harbor to the Columbia River until and unless paired trawling and entrainment measurements provide site-specific data to validate the function. The appropriate site-specific data to evaluate the applicability of the Grays Harbor entrainment function for the Columbia River are not presently available.

Another required input to the DIM is data on crab density by size class and season for the different reaches to be dredged. There is no recent data of this type from the Columbia River. The crab density data from the Columbia River was taken in the 1980's for different purposes, and spatial coverage is sparse for reaches of the Columbia River to be dredged (McCabe et al. 1986, 1989).

To gain perspective on the dredge entrainment impacts using currently available data, a modified DIM (Figure 6) was used in the analysis here. The modified DIM does not depend on the entrainment function from Grays Harbor or trawl data from the Columbia River. The modification employs the entrainment rates directly observed on a Corps dredge in the Columbia River in summer 2002.

1.4 Overview of Entrainment Measurements, Projections, and Scenario Analyses

This document reports the results of three tasks:

- Direct measurements of crab entrainment in the field
- Projections of crab entrainment during the dredging planned for the Channel Improvement Project

- Modeling and scenario analysis of the influence of salinity on crab distribution

In the first task, the scientific team made direct measurements of crab entrainment rates on the Corps' Dredge *Essayons*, which is equipped with a basket sampler into which a portion of the dredged materials entering the vessel's hopper can be diverted to obtain entrainment samples. During the summer 2002 maintenance dredging, the scientific team sampled at the mouth of the Columbia River (MCR), Desdemona Shoals, Upper Sands, and Miller Sands (Figure 7). Although some results from crab entrainment measurements from the MCR will be discussed here, the MCR studies will be fully detailed in a separate report. The first task also included measurements of fluid flow in the piping to the dredge's basket sampler to determine the factors for sample volumes in calculations of entrainment rates. A modified DIM used the data from the first task to calculate the Adult Equivalent Loss (AEL) and Loss to Fishery (LF) for the volume of materials dredged at each location in summer 2002. The second task used the entrainment rates measured in the summer of 2002 to make projections of crab entrainment using the modified DIM with the dredged volumes planned for the Channel Improvement Project. The third task used a model for the relationship between salinity and crab density to assess relative crab distribution under several scenarios of salinity intrusion in the Columbia River Estuary. The third task included an analysis of the relationship between entrainment rate and bottom salinity using the summer 2002 data.

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MATERIALS AND METHODS

1.5 Methods for Direct Measurements of Entrainment Rates

1.5.1 Summary of Field Activities

MSL researchers directly measured crab entrainment aboard the Corps' Dredge *Essayons* in June 2002 and from July through October 2002 when the dredge was engaged in maintenance and operational dredging of the Columbia River (Table 5, Figure 7). This document reports results from sampling at Desdemona Shoals, Upper Sands, and Miller Sands. Detailed results from the sampling in the MCR are reported separately. The *Essayons* is equipped with a special basket sampler, into which a portion of the dredged materials entering the vessel's hopper can be diverted. To support the calculations of the volume of dredged material sampled by the basket sampler, measurement of the fluid flow in the pipe leading to the basket sampler was conducted in September 2002.

1.5.2 Statistical Design of Field Sampling

Before the start of field measurements to determine entrainment rates for Dungeness crab on the Columbia River, the study team developed sampling designs and data analysis plans for the June sampling and for the July to October sampling. To aid in the development of the June sampling design, the Portland District provided previously collected raw data on entrainment rates from the study of Larson (1993). Examination of the Larson (1993) data revealed that the entrainment rates exhibited three major variance components: 1) Day-to-day variability, 2) Load-to-load variability, and 3) Sample-to-sample variability within loads. The day-to-day variability was the dominant variance component. Because day-to-day variability dominated, the study team recommended that sampling occur every day of the five days of dredging projected for June 2002. To select appropriate sampling rates to address load-to-load and sample-to-sample variances, coefficients of variation (CV) for various combinations of sampling rates were calculated based on the Larson (1993) data (Table 6). A CV of 0.125 was required for the estimates of entrainment in order to be 95% confident of being within $\pm 25\%$ of the true value. To obtain the desired precision for the June 2002 sampling, the study team sampled each day of dredging, selecting half the loads at random and sampling 10 basket samples per load.

To develop the sampling design for the summer 2002 sampling, the results of the June 2002 were examined. Again, the day-to-day variability proved to be the dominant variance component. To select appropriate sampling rates to address load-to-load and sample-to-sample variances for the summer 2002 sampling, coefficients of variation (CV) for various combinations of sampling rates were calculated based on the June 2002 data (Table 7). A CV of 0.125 was required for the estimates of entrainment in order to be 95% confident of being within $\pm 25\%$ of the true value. To obtain the desired precision for the summer 2002, the study team sampled each day of dredging, selecting half the loads at random and sampling 3 basket samples per load.

1.5.3 Methods for Entrainment Observation

Researchers conducted crab entrainment studies aboard the Corps' Dredge *Essayons* in June and from July through October 2002 when the dredge was engaged in maintenance and operational dredging of the Columbia River (Table 5, Figure 7).

The data for estimation of crab entrainment rates were derived from a two-stage sampling scheme. The first stage involved the random sampling of approximately half (50%) of the loads collected by the dredge. The second stage involved the random sampling of dredged material within the selected loads. Hence, there were two aspects to the sampling protocol: (1) the random selection of loads, and (2) the random selection of "basket" samples within a load. In June, 9 or 10 basket samples per load were processed. From July to October, 3 basket samples per load were processed. These basket samples were randomly distributed through the period of load collection, which typically took about an hour.

Four sets of data sheets were used to record field data. These included load by load records, sample records, within-load records, and a daily log. The load by load record sheet included a randomly determined schedule constructed to indicate which loads to sample and which not to sample. Total load volumes [cubic yards (cy)] and distances (ft) were recorded onto these sheets for all loads during the duration of the survey, whether sampled or not; this information was obtained from the *Essayons*' dredge logbook. Sample records were used to record data on individual basket samples taken within a load, including numbers, size, and sex of Dungeness crab entrained. Within-Load records summarized the crab, fish, and mollusks enumerated in each basket sample, along with the volume of the basket sample. Finally, the daily log was used to record pertinent weather conditions, personnel involved, dredge operations, and deviations from normal operating procedures (e.g., repairs, gear modification).

On-deck sampling proceeded according to the following procedures. When ready to sample, the researcher communicated to the vessel bridge via radio to request the use of hydraulics to operate the crab basket sampler and gate valve, and for closure of starboard valve V17 (Figure 8). This configuration allowed the researcher to sample approximately ½ the volume of a single drag arm, or ¼ the total volume of material being loaded by the dredge. The hydraulic gate valve was operated on-deck by the researcher to allow dredged material to flow to the basket sampler. A time interval of approximately 30 seconds (45 seconds at MCR) usually yielded a manageable volume of dredged materials sample. Therefore, standard valve-timing procedures were as follows (time period in parentheses): the valve was opened (from 0 to 11 sec), valve remained fully open until 15-second mark (from 11 to 15 sec), and valve was closed (from 15 to 28 sec). In all cases, the start time (hh:mm) and time increments (seconds) at which valve closure was initiated and fully closed were recorded. Calculation of sample volumes is explained in a later section of this report.

The basket sampler was then tilted on its side using the second hydraulic valve. The researcher communicated to the bridge that the hydraulics were no longer required and

received information on the average load rate and ship speed. From July through October, the researcher measured and recorded the temperature (°C) and salinity (o/oo) of pumped seawater obtained from a catch pan under the cage using a YSI Model 556 multiple probe system (MPS). Finally, the basket sampler was emptied of sample using 5-gallon buckets, and the sample dumped onto the sorting table.

Researchers sorted whole and parts of living organisms from the sample and identified and enumerated individuals from the following taxa: crab (*Cancer magister* and other species), shrimp (e.g., *Crangon* spp.), razor clam, and all fish species. In cases where an animal other than crab was crushed or pieces were collected, the animal was counted only if the head was present (See details below on quantifying crushed crab). The relative abundance of other species (e.g., olive snail, polychaetes) was noted. Total length (length from the tip of the upper jaw to the end of the caudal fin) of fishes was also recorded.

The carapace widths (CW) of all crabs were measured using calipers, and larger crabs were sexed. If ½ a carapace was present, this was measured and total CW was estimated. In cases where a crab was crushed or pieces were collected, we consistently quantified only those crabs for which we collected more than ½ carapace, or other matched pieces (e.g., telson, legs, chela, thorax) constituting 1/3 of a crab. When these criteria were not met (e.g., only 2 legs collected), the presence of crab pieces was noted qualitatively (“YES”) under the UID (unidentified) crab column on the record sheet. All crabs and crab pieces were dumped into the dredge hopper to minimize duplicate counts on subsequent passes.

Finally, the sediment type (e.g., sand, mud, gravel, shell) and vegetation was noted, the basket sampler was cleaned with a pressure washer, and the process restarted. All data sheets were completed and errors corrected with a single line that was initialed and dated. At the end of each load, researchers reviewed the data sheets for completeness, accuracy, and legibility.

1.5.4 Modifications to Standard Sampling Procedures

Slight changes were made to sampling procedures on some dates to maximize data collection during limited sampling windows or mechanical delays. When a mechanical issue prevented sampling of a load scheduled to be sampled, researchers skipped ahead on the random number schedule to the next load to be sampled when operations returned to normal.

There were also situations due to extreme ebb tides or equipment damage when only a single drag arm was used to dredge the channel. In these cases, the volume of dredged material flowing into the vessel was reduced by ½. To maintain adequate sample volumes flowing to the basket sampler, the port side valves (V16 and V17) that distributed loads into the hold were closed when sampling occurred (Figure 8).

1.5.5 Calculating Sample Volume

In previous studies, the sample volumes used to estimate crab entrainment were based on full flows of a 66 cm discharge pipe over a 30-60 second sampling interval (Larson 1993). Coarse estimates of mean flow rates of the discharge pipes were calculated on a load-by-load basis by dividing total pumping time (PT) by total load (cy) (see formulae on p. 7, Larson 1993). Therefore, sample volume was based on flow rate multiplied by sampling interval (total time valve was open).

Observations made during our June sampling effort suggested that procedures for calculating the sample volumes needed to be refined to take into account the depth of fluid in the pipe and the timing of opening and closing the hydraulic gate valves. Flow volumes associated with the dredge hopper discharge pipes were calculated using the following methods.

Computation of the area based on the depth (or degree to which the gate is opened) is based on the following:

The ratio of instantaneous cross-sectional area (A_i) to the half-pipe cross-sectional area (A_{max}) is used to proportionally reduce the full-pipe flow (Q_{max}) to estimate the instantaneous flow Q_i

$$Q_i = A_i / A_{max} * Q_{max}$$

The time series of Q_i are time-integrated to get a cumulative volume $V =$ sum of ($Q_i * dt$) over the 28 second period, or

$$V = \text{sum of } A_i / A_{max} * Q_{max} * dt.$$

But A_{max} , Q_{max} and dt do not change so that

$$V = dt * Q_{max} / A_{max} * \text{sum of } A_i$$

The effective sampling interval, $T_{eff} = V / Q_{max}$, or

$$T_{eff} = (dt * Q_{max} / A_{max} * \text{sum of } A_i) / Q_{max}$$

This reduces to $T_{eff} = dt * (\text{sum of } A_i) / A_{max}$ (hence no functional connection to input Q).

This allows for estimation of T_{eff} with some assumptions:

- After the gate is opened further than half-way, there is no longer an influence on flow
- The non-linear processes are neglected. No friction, no contraction, no acceleration

- The cross-sectional average velocity is uniform regardless of how far the gate is opened; flow rate is only a function of cross-sectional area available for flow. The average cross-sectional velocity is the same when the pipe is half-full or barely open.

The estimate of effective sampling period (Teff) is based upon the rate the gate valve is opened, the time it stays open, and the rate it is closed; it is not sensitive to overall flow rate. Flows are reduced during the first half of both the gate valve opening and closing intervals. Assuming the pipe is ½ full and standard valve-timing procedures (opening from 0 to 11 sec, fully open from 11 to 15 sec, closing from 15 to 28 sec), the effective sampling period is 21.4 seconds.

Sample volume was calculated by multiplying effective sampling time (t) by mean load rate (cy/t) of the discharge pipe feeding the basket sampler. As in Larson (1993), mean load rates of the discharge pipes were calculated on a load-by-load basis by dividing total pumping time (PT) by total load volume in cy (Y). Flow measurements were conducted to clarify what proportion of the total flow (load rate) was diverted into the crab sampler.

1.5.6 Flow Measurements

Flow measurements were conducted to verify the assumption that the basket sampler was receiving 25% of the total load of dredged materials. A FLO-DAR (Model 460 / Data Logger Serial Number: 46000141 / Meter Serial Number: BA0239) open channel, non-contact, radar flow meter was used to estimate velocity, level, and flow of the slurry contained within the pipe. Specifications and accuracy of the instruments were as follows:

Velocity Measurement

Method: Radar

Range: 0.75 to 20 ft/s

Accuracy: ±0.1 ft/s (±0.5%)

Level Measurement

Method: Ultrasonic

Operating Range: 0.25 to 60 in.

Temperature Compensated

Accuracy: ±0.25 in. (1%)

Flow Measurement

Based on Continuity Equation.

Accuracy: ±5.0% of reading typical where flow is in a channel with uniform flow conditions.

The sensor was mounted approximately 5 ft downstream of the basket sampler valve, by cutting a hole 6 inches wide by 20 inches long centered on the 26-inch inside diameter pipe. Flanges were welded on top of the pipe, raising the sensor 5 inches off the top of

the pipe. Five inches were used as the offset in the data collection for pipe level measurement. The sensor was mounted and connected to data loggers, which in turn were connected to a Dell Inspiron 3800 computer to monitor and record real time measurements.

Initial readings were taken to establish best flow conditions by closing valves 17 starboard and 16 starboard with the basket sampler valve open. This allowed for total starboard dredged materials flow past the sensor. Flow measurements were taken with both port and starboard dredge motors balanced at 250, 275, and 300 rpm. The optimum setting was found at 275 rpm, with 300 rpm providing too much flow and 250 rpm causing excessive flow pulsing.

Flow measurements were compared between two different piping configurations (total starboard flow vs. normal configuration during crab sampling). To measure total starboard flow, measurement data was logged for approximately 10 to 15 minutes with the dredge motor at 275 rpm, the 17 starboard and 16 starboard valves closed, and the basket sampler valve open. To measure flows associated with the typical piping configuration observed during crab sampling, the 16 starboard valve was reopened and measurements logged for approximately 10 to 15 minutes. These flow measurements were then repeated several times over the course of normal dredging operations. When in normal configurations for crab sampling, the pipe was always a minimum of half-full.

Instrument readings indicate that flow coming into the crab basket sampler as a proportion of total flow coming onboard was 0.26 with a 95% Confidence Interval (CI) from 0.23 to 0.29. These results provided no evidence to reject the value of 0.25 used by Larson (1993). Therefore, all calculations of sediment load and crab entrainment use factor of 0.25 to correct for the proportion of total flow (load rate) diverted into the basket sampler.

1.5.7 Calculation of Adult Equivalent Loss and Loss to Fishery for Summer 2002 Dredged Volumes

To calculate Adult Equivalent Loss (AEL) and Loss to the Fishery (LF) for the dredged volumes accomplished in summer 2002, we used a modified DIM that does not depend on the entrainment function from Grays Harbor or previous trawl data from the Columbia River. The modification employs the entrainment rates directly measured on the Corps' Dredge *Essayons* in the Columbia River. The approach (Figure 6) includes the following steps:

1. Use entrainment rates (R as crabs per cy) directly measured on the dredge (no need to reference trawl density).
2. Multiply these entrainment rates by the dredged volumes to give the number of crabs entrained (E as number of crab).
3. Apply the post-entrainment mortality rates from Wainwright et al. (1992) to give immediate losses.

4. Apply the natural survival rates from Wainwright et al. (1992) to give Adult Equivalent Loss (AEL as number of crab) to midwinter Age 2+. (To obtain the AEL at Age 2+ for Age 3+ crab, the number of Age 3+ crab was back-calculated to its equivalent at Age 2+ using the reciprocal of the survival rate.)
5. Apply a survival rate of 45% to midwinter Age 3+ (Armstrong et al. 1991) to give AEL at Age 3+.
6. Apply observed sex ratios and a harvest rate of 70% (Wainwright et al. (1992) to give loss to the fishery (LF as number of crab).
7. Calculate variance and 95% confidence intervals for E, AEL, and LF.
8. Compare the loss to the fishery (LF) to the landings (WDFW and ODFW) from the Columbia River Area to give perspective on the estimated impact.

1.5.8 Statistical Analyses and Calculation of Variance and Confidence Limits

Estimating Numbers of Entrained Crabs

In a random sample of loads, crab entrainment densities were estimated from a random sample of dredged material. Hence, the sampling design consists of a two-stage sampling scheme; Stage 1: Random sample of h of H loads and Stage 2: Random sample of dredged materials based b of B basket samples. The estimator of total entrainment for a specific age-class (i.e., size class) of crabs can be expressed as follows:

$$\hat{E}_i = \frac{\sum_{j=1}^h \left[\frac{V_j}{b_j} \sum_{l=1}^{b_j} x_{ijl} \right]}{\sum_{j=1}^h V_j} \cdot \sum_{j=1}^H V_j \quad (1)$$

where

x_{ijl} = number of age class i ($i = 1, \dots, A$) crabs/ Y^3 measured in the l th basket sample ($l = 1, \dots, b_j$) in the j th load ($j = 1, \dots, h$);

b_j = number of basket samples observed in the j th load ($j = 1, \dots, h$);

h = number of loads selected for sampling of crab density;

H = total number of loads at a dredged location;

V_j = total volume of dredged materials in the j th load ($j = 1, \dots, h$).

In turn, x_{ijl} can be expressed in terms of the number of crabs counted and the volume of the l th basket sample of the j th load where

$$x_{ijl} = \frac{C_{ijl}}{w_{jl}}$$

where

c_{ijl} = number of age class i crabs ($i = 1, \dots, A$) in the l th basket sample ($l = 1, \dots, b_j$) in the j th load ($j = 1, \dots, h$);
 w_{jl} = volume of the material sampled in the l th basket sample ($l = 1, \dots, b_j$) in the j th load ($j = 1, \dots, h$).

As such, the estimator of total crab entrainment for age class i crabs ($i = 1, \dots, A$) can be expressed as

$$\hat{E}_i = \frac{\sum_{j=1}^h \left[V_j \frac{\sum_{l=1}^{b_j} c_{ijl}}{b_j} \right]}{\sum_{j=1}^h V_j} \cdot \sum_{j=1}^H V_j. \quad (2)$$

Estimators (1) and (2) will be the same if sample values $w_{ij} = w_i$ are equal within a load. Because sample volumes varied between basket samples, estimator (2) is the preferred estimator of total entrainment.

The variance of \hat{E}_i is found by taking the variance in stages. The variance of \hat{E}_i (Equation 2) can then be expressed as follows:

$$Var(\hat{E}_i | E_i) = H^2 \left(1 - \frac{h}{H} \right) \frac{\sum_{j=1}^H (V_j R_{ij} - R_i V_j)^2}{h(H-1)} + \frac{H}{h} \sum_{j=1}^H [V_j^2 \cdot Var(\hat{R}_{ij})] \quad (3)$$

where

$$R_{ij} = \frac{\sum_{l=1}^{B_j} c_{ijl}}{\sum_{l=1}^{B_j} w_{jl}} = \text{true density of age class } i \text{ crabs (i.e., crabs/Y}^3\text{) in the } j\text{th load } (j = 1, \dots, H);$$

$$R_i = \frac{\sum_{j=1}^H R_{ij} V_j}{\sum_{j=1}^H V_j} = \text{true density of crabs (i.e., crabs/Y}^3\text{) across all } H \text{ levels};$$

$$Var(\hat{R}_{ij}) = \frac{\left(1 - \frac{b_j}{B_j} \right) \sum_{l=1}^{B_j} (c_{ijl} - R_{ij} w_{jl})^2}{b_j \bar{w}_j (B_j - 1)};$$

and where

$$\bar{w}_j = \frac{\sum_{l=1}^{B_j} w_{jl}}{B_j} = \text{average volume of basket sample in the } i\text{th load};$$

B_j = total number of possible basket samples within the j th load.

Variance formula (3) cannot be used to analyze the field data because it is dependent upon unknown parameter values. Instead, an estimated variance must be calculated and used in confidence interval estimates.

An approximately unbiased variance estimator for \hat{E} can be written as follows:

$$\text{Var}(\hat{E}_i | E_i) = H^2 \left(1 - \frac{h}{H}\right) \frac{\sum_{j=1}^h (V_j \hat{R}_{ij} - \hat{R}_i V_j)^2}{(h-1)} + \frac{H}{h} \sum_{j=1}^h V_j^2 \cdot \text{Var}(\hat{R}_{ij}) \quad (4)$$

where

$$\hat{R}_{ij} = \frac{\sum_{l=1}^{b_j} c_{ijl}}{\sum_{l=1}^{b_j} w_{jl}},$$

$$\hat{R}_i = \frac{\sum_{j=1}^h \left[V_j \frac{\sum_{l=1}^{b_j} c_{ijl}}{b_j} \right]}{\sum_{j=1}^h V_j}, \quad (5)$$

$$\text{Var}(\hat{R}_{ij}) = \frac{\left(1 - \frac{b_j}{B_j}\right) \sum_{l=1}^{b_j} (c_{ijl} - \hat{R}_{ij} w_{jl})^2}{b_j \bar{w}_j^2 (b_j - 1)},$$

which, when B_j is very large, simplifies to

$$\text{Var}(\hat{R}_{ij}) = \frac{\sum_{l=1}^{b_j} (c_{ijl} - \hat{R}_{ij} w_{jl})^2}{\bar{w}_j^2 b_j (b_j - 1)},$$

and where

$$\bar{w}_j = \frac{\sum_{l=1}^{b_j} w_{jl}}{b_j}.$$

Asymptotic $(1-\alpha)$ 100% confidence interval estimates for \hat{E}_i can be calculated as

$$\hat{E}_i \pm Z_{1-\frac{\alpha}{2}} \sqrt{\text{Var}(\hat{E}_i | E_i)}.$$

Estimating the Entrainment Rate

The entrainment rate (R_i) for the i th age class of crabs can be defined by Equation (5) or equivalently as the ratio of the total number of crabs entrained to the total volume of dredged material collected where

$$R_i = \frac{E_i}{\sum_{j=1}^H V_j}.$$

The entrainment rate (R_i) can be estimated by the ratio

$$\hat{R}_i = \frac{\hat{E}_i}{\sum_{j=1}^H V_j} \tag{6}$$

with associated variance estimator

$$\text{Var}(\hat{R}_i | R_i) = \frac{\text{Var}(\hat{E}_i | E_i)}{\left[\sum_{j=1}^H V_j \right]^2}. \tag{7}$$

Estimating Adult Equivalent Loss (AEL)

The estimate of adult equivalent loss (AEL) for the Dungeness crab entrainment can be expressed as follows:

$$\text{AEL} = \sum_{i=1}^A \hat{E}_i \cdot \hat{M}_i \cdot \hat{S}_i \tag{8}$$

where

- \hat{E}_i = estimate of total crabs entrained of age class i ($i = 1, \dots, A$);
- \hat{M}_i = estimate of direct mortality associated with the dredging operation on crabs entrained of age class i ($i = 1, \dots, A$);
- \hat{S}_i = estimate of the survival probability from age class i ($i = 1, \dots, A$) to age of interest;
- A = number of age classes (i.e., 2+ or 3+).

A

Estimates of \hat{M}_i and \hat{S}_i used in the assessment did not have associated variance estimators. Hence, the contribution of $Var(\hat{M}_i)$ and $Var(\hat{S}_i)$ could not be propagated to the overall variance of the AEL estimates. Instead, \hat{M}_i and \hat{S}_i were treated as known constants when calculating the variance of \bar{AEL} . In which case,

$$Var(\bar{AEL}) = \sum_{i=1}^A \left[Var(\hat{E}_i | E_i) \cdot \hat{M}_i^2 \cdot \hat{S}_i^2 \right]. \quad (9)$$

Equation (9) will underestimate the true variance of the AEL estimates when \hat{M}_i and \hat{S}_i are measured with error.

Estimating Loss to Fishery (LF)

The loss to the fishery (LF) of harvestable crabs was estimated by the quantity

$$\bar{LF} = \hat{H} \cdot \sum_{i=1}^A \hat{G}_i \hat{E}_i \hat{M}_i \hat{S}_i \quad (10)$$

where

- \hat{G}_i = estimated fraction of the i th age class composed of males,
- \hat{H} = estimated probability of harvesting a male crab in the Dungeness fishery.

\hat{H}

Again, assuming the values of \hat{G}_i and \hat{H} are known constants, the variance of \bar{LF} can be estimated by the formula

$$Var(\bar{LF}) = \hat{H}^2 \cdot \sum_{i=1}^A \left[Var(\hat{E}_i | E_i) \cdot (\hat{G}_i \cdot \hat{M}_i \cdot \hat{S}_i)^2 \right]. \quad (11)$$

Equation (11) will underestimate the true variance of \bar{LF} when H and G_i are measured with error.

1.6 Methods for Projections of Impacts using Modified DIM

Projections of crab AEL and LF associated with future construction dredging were made based on work quantity calculations provided by the USACE Portland District (Table 8). The total dredging prism volumes for each location include two increments: 1) dredging to bring the channel to the 40-foot depth currently authorized and 2) new work dredging to channel from the 40-depth to the new 43-foot depth. In all cases, projections are compiled by age class (age 2+ and 3+) and crab sex. These projections were calculated for each of the following upriver bar areas: Desdemona (Lower and Upper combined), Flavel Bar, Upper Sands, and Tongue Point.

For each bar area, we employed the DIM approach outlined above with two modifications. First, entrainment rates (R, as crabs per cy) and sex ratios corresponded to those measured at a particular bar area in 2002. Flavel Bar and Tongue Point were not sampled in 2002. For these two areas, we employed the entrainment rates for sampled locations both upriver and downriver from the areas of interest. Second, entrainment rates \otimes were multiplied by the projected dredged volumes (Table 8) to yield the number of crabs entrained (E, as number of crab). The maintenance and deepening projections were run for each of the following cases:

Projected Volumes – Upriver Bar Area	Data Source – Entrainment Rate and Sex Ratio
Desdemona	Desdemona, June 2002
Desdemona	Desdemona, Sept 2002
Flavel Bar	Desdemona, June 2002
Flavel Bar	Desdemona, Sept 2002
Flavel Bar	Upper Sands, Sept 2002
Upper Sands	Upper Sands, Sept 2002
Tongue Point	Upper Sands, Sept 2002
Tongue Point	Miller Sands, Oct 2002
Miller Sands	Miller Sands, Oct 2002

Projections of crab AEL and LF associated with future maintenance dredging were made based on work quantity calculations provided by the USACE Portland District (Table 9). DIM runs were made for Year 1 and Year 20 following construction. The maintenance dredging volumes are expected to decline over the 20 years following construction. The worst-case assumptions were used to project entrainment during maintenance dredging.

1.7 Approach for Analysis of Salinity and Crab Distribution

To assess the influence of salinity on crab distribution, we applied the salinity-crab density model developed from the Stevens and Armstrong (1984) data (described in Introduction section above) to several scenarios for salinity intrusion into the Columbia

River Estuary. The salinity-crab density model was developed for Ages 1+ and older and does not address Age 0+. The scenarios examined include the following:

- Six conditions from Jay and Smith (1990) (Table 3) that cover salinity intrusion under low and high river flow and spring and neap tides
- The median under low river flow conditions from Jay and Smith (1990) (Table 3)
- Bottom salinity forecasts from CORIE/ELCIRC for May and September of 2002

The above scenarios were used to develop a series of distributions of bottom salinity by river mile along the South Channel. The salinity-crab density model was used to forecast the relative crab density by river mile for each distribution of bottom salinity by river mile. Predicted crab density is then plotted by river mile.

In addition to the assessment of the scenarios for salinity intrusion, we also regressed the entrainment rates determined for each dredged area during the summer of 2002 against two measures of bottom salinity for the dredged area. For the entrainment rates in June taken at Desdemona Shoals, we used the bottom salinities taken from the bottom CTD deployed at CORIE Station RED2, the station closest to Desdemona Shoals. For all the other areas and times, we used the bottom salinities taken from the dredged materials during the crab entrainment sampling. The two measures of salinity used were the percentage of salinity observations at and above 32 o/oo and the percentage of salinity observations at and below 16 o/oo.

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RESULTS

1.8 Direct Measurements of Crab Entrainment

While the Corps' Dredge *Essayons* was conducting maintenance dredging in the Columbia River, the scientific team made direct measurements of crab entrainment at Desdemona Shoals in June and September 2002, at Upper Sands in September, and at Miller Sands in October (Table 5). The team sampled 66 of the total of 123 loads dredged at these locations. The total number of basket samples taken at these locations was 348. The data from these samples appears in Appendix A.

1.8.1 Entrainment Rates ®

Dungeness crabs were found in the entrainment samples at Desdemona Shoals and Upper Sands; however, no crab or crab parts were found in the 140 basket samples taken at Miller Sands in October 2002. The total entrainment rates for all age classes varied from zero at Miller Sands to 0.224 crab/cy at Desdemona Shoals in June 2002 (Table 10). At Desdemona Shoals, June entrainment samples were largely composed of Age 1+ crabs, but by September entrainment samples were dominated by Age 2+ crabs (Table 10). At Upper Sands, only Age 0+ and Age 1+ crabs were found in the entrainment samples. Other species entrained in moderate numbers included *Crangon* shrimp, Pacific sand lance (*Ammodytes hexapterus*), and eulachon (*Thaleichthys pacificus*) (Appendix A5).

1.8.2 DIM Results for Dredged Volumes Accomplished in Summer 2002

The results of applying the DIM for dredged volumes accomplished during summer 2002 are summarized in Table 11 and Table 12, and detailed in Appendix A. The lowest dredge impacts were observed at Miller Sands, and the highest at Desdemona Shoals in June. Crab AEL at Age 2+ ranged from zero at Miller Sands, to 6,314 crabs (95% Confidence Interval (CI) of 5,403 to 7,225 crabs) at Desdemona Shoals in June 2002. Loss to the fishery ranged from zero at Miller Sands, to 1,194 crabs (95% CI of 1,004 to 1,384 crabs) at Desdemona in June 2002. The AEL at Age 2+ and the loss to the fishery at Upper Sands were less than 1% of the AEL and LF at Desdemona Shoals in June 2002.

1.9 Projections of Crab Entrainment for Channel Improvement Project

The Channel Improvement Project involves planned construction dredging at four locations between RM3 and RM20: Desdemona Shoals, Flavel Bar, Upper Sands, and Tongue Point (Tables 8 and 9). Crab entrainment, AEL at 2+, AEL at 3+, and loss to fishery (LF) were projected for two construction increments (dredging to 40' and from 40 to 43') and four annual maintenance scenarios (40' Channel Maintenance under the No Action Alternative in Year 1 and Year 20; 43' Channel Alternative Maintenance under the Proposed Plan in Year 1 and Year 20) for these locations using the entrainment rates directly measured in the summer of 2002. In total, nine sets of projections were run

(Appendix B). Two sets of projections were conducted for Desdemona Shoals based on June and September 2002 entrainment data, respectively. Sets of projections were also run for Upper Sands and Miller Sands. Three sets of projections for Flavel Bar and two for Tongue Point were made using the entrainment rates measured from the nearest areas up and down river of the area of interest.

The results of construction projections are summarized in Table 13 (dredging to 40') and Table 14 (dredging from 40' to 43'), and detailed in Appendix B. In general, the lowest projected AEL at age 2+ was observed at Tongue Point, whereas the highest projected AEL at 2+ were observed at Flavel Bar. Construction projections for AEL at Age 2+ range from zero at Tongue Point using the Miller Sands entrainment rates, to 117,834 crabs (95% CI of 71,066 to 164,602 crabs) at Flavel Bar using the September Desdemona Shoals entrainment rates. Similarly, loss to the fishery from construction ranged from zero at Tongue Point using the Miller Sands entrainment rates, to 18,559 crabs (95% CI of 11,193 to 25,925 crabs) at Flavel Bar using the September Desdemona entrainment rates.

The worst-case (highest AEL and LF) and best-case (lowest AEL and LF) projections during construction dredging are summarized by location in Table 15. Estimated total AEL at 2+ ranges from 20,772 to 114,640 crabs during construction dredging to 40' (Table 15). Most of this loss would occur in Desdemona Shoals under either the best or worst case assumption. Estimated total AEL at 2+ ranges from 18,039 to 166,888 crabs during construction dredging from 40' to 43'. Flavel Bar contributes the greatest portion of this loss (117,834 crabs) under the worst-case assumption, whereas Desdemona Shoals contributes the greatest portion (16,023 crab) using the best-case assumption. Projected overall AEL at 2+ from both increments of construction dredging ranges from 38,811 to 281,528 crabs. Overall projected losses to the fishery from construction dredging range from 7,252 to 44,342 crabs.

Projections of crab AEL at 2+ and LF under annual maintenance dredging for the No Action Alternative (40' Channel) and the Proposed Plan (43' Channel) are summarized by location and year in Table 16. These values reflect the following worst-case (highest loss) projections: Flavel Bar (Entrainment rate [R] from Desdemona September), Desdemona (R from Desdemona September), Tongue Point (R from Upper Sands), and Upper Sands (R from Upper Sands). Projected losses from maintenance dredging generally mirror estimated dredging volumes, which are predicted to be higher in Year 1 than in Year 20.

For maintenance dredging under the No Action Alternative (40' Channel), estimated total AEL at 2+ ranges from 44,643 crabs in Year 1 to 25,503 crabs in Year 20 (Table 16). Most of this loss is predicted to occur at Flavel Bar in both Year 1 (40,295 crab) and Year 20 (21,155 crab). For maintenance dredging under the Proposed Plan (43' Channel), the estimated total AEL at 2+ ranges from 56,840 crabs in Year 1 to 25,612 crabs in Year 20. Again, Flavel Bar contributes the greatest portion of this loss in both Year 1 (50,369 crabs) and Year 20 (21,155 crabs). For maintenance dredging under the Proposed Plan

(43' Channel), projected losses to the fishery are 8,953 and 4,035 in Year 1 and 20, respectively.

1.10 Analysis of Salinity and Crab Distribution

Using the Jay and Smith (1990) conditions, modeling indicates that the highest crab densities are seaward of RM10. Of the six conditions modeled (Table 3), the highest crab densities are seaward of RM5 with moderate crab densities at RM10 under maximum intrusion for two conditions: 1) low river flow and spring tides, and 2) high river flow and spring tides (Figure 9). The condition showing the furthest upriver extent of crab densities is for maximum intrusion under low river flow and neap tides. Under this condition for furthest upstream extent of crab densities, predicted crab density at RM18 is about 8% of that at RM0. For the field salinity measurements of Jay and Smith (1990), the low river flows ranged from 120 to 150 Kcfs, and the high river flows, from 535 to 570 Kcfs. Under the median of the low flow conditions of the Jay and Smith (1990) conditions, crab densities predicted at and above RM10 are less than 1% of those predicted at RM0 (Figure 10).

From October 2001 to October 2002, the river flow ranged from slightly less than 100 Kcfs to a brief peak of about 430 Kcfs (Figure 3). Plots of the bottom salinities forecast by the CORIE/ELCIRC model for May 21, 2002 and September 1, 2002 (Figure 11) show that salinity intrusion was greater under a river flow of 133 Kcfs in September than under a river flow of 292 Kcfs in May. For the May flow, predicted crab density at RM13 was less than 1% of that predicted at RM1 (Figure 11). For the September flow, predicted crab density at RM13 was about 9% of that at RM1.

Site-specific data from the Columbia River in summer 2002 support the concept that salinity influences crab distribution. In summer 2002, entrainment rates fell as the bottom waters became fresher (Table 15). At Miller Sands, where bottom salinities were less than 16 o/oo for 100% of the salinity measurements, no crab or crab parts were entrained in any of the 140 basket samples. In the MCR, where bottom salinities were above 28 o/oo for 98% of salinity measurements, crabs were consistently entrained over the course of the summer sampling. For all age classes, 1+ and older, regression analysis showed that the natural logarithms of the entrainment rate for each dredged area were significantly related to the percentage of salinity observations less than 16 o/oo but not to the percentage of salinity above 32 o/oo (Table 16). For age 1+ crabs alone, the natural logarithms of the entrainment rates were not significantly related to either measure of salinity. At Desdemona Shoals, age 1+ crabs had a higher entrainment rate ($R = 0.193$ crab/cy) in June 2002 when bottom waters were fresher (16% of salinity observations less than 16 o/oo) than the rate ($R = 0.022$ crab/cy) in September when the bottom waters were saltier (0 % of the salinity observations less than 16 o/oo). For age 2+ and older, regression analysis revealed that the natural logarithms of the entrainment rates were significantly related to both the percentage of salinity observations above 32 o/oo and the percentage below 16 o/oo (Table 16). The parameter explained explaining the highest percentage of the variation in regressions was the percentage of salinity observations less than 16 o/oo.

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DISCUSSION

The entrainment rates reported here constitute a major step in quantifying crab entrainment in the Columbia River Estuary above RM3. The previous measurements of entrainment rates in the Columbia River were much more limited. For example, entrainment rates measured by Larson (1993) were restricted to the Mouth of the Columbia River, whereas the pilot sampling by PIE in spring 2002 at Desdemona Shoals was restricted to one day.

Entrainment rates (in areas where crab occurred) measured in this report were from the middle of the range to the low end of those reported in previous studies. Entrainment rates for all age classes reported here for the summer of 2002 ranged from 0.020 to 0.224 crabs per cy for locations above RM4 and below RM20 (Table 9). In comparison, Larson (1993) reported annual average entrainment rates in the MCR (below RM3) ranging from 0.32 to 10.78 crabs per cy for 0+ crab and from 0.03 to 0.18 crabs per cy for 1+ and older crab. Other studies in the Grays Harbor estuary reported entrainment rates that ranged from 0.03 to 0.5 crabs per cy (Wainwright et al. 1992). The rates of Wainwright et al. (1992) were derived from 14 surveys of 2 to 3 days each conducted over several years.

It should be noted that the entrainment rates reported and used here are based on sampling conducted during the summer months of a single year. Crab abundance in the Columbia River and other estuaries is known to vary by season, and from year to year within a season. For example, we attribute the relatively few 0+ crab found in the summer 2002 samples to not having sampled in May and early June when large numbers of 0+ crab enter the lower estuary (McCabe et al. 1986, 1989; Larson 1993). McCabe et al. (1989) found that the density of 0+ crab at Flavel Bar had declined substantially (0 to 10 crabs/ha) by July in each of the four years they conducted their studies.

Entrainment rates also may change at a particular location over time, based on crab movement patterns that are likely influenced by season, salinity, population structure, and behavioral interactions. For example, the entrainment rate for all age classes at Desdemona Shoals declined from 0.224 crabs per cy in June, to 0.120 crabs per cy in September (Table 9). Age 1+ crab contributed the most to the higher June entrainment rate, while the entrainment rate for 1+ crab in September was about 11% of that in June. Similarly, McCabe et al. (1989) found 1+ crab (their Size Class II) at Flavel Bar to have a 4-year average density of 517 crabs/ha in June and 35 crabs/ha in September (about 6% of the June average). This change in age 1+ crab entrainment rates at Desdemona Shoals could be related to seasonal migration patterns. Armstrong et al. (1987) found that some component of the age 1+ crab population entered the Grays Harbor Estuary from the ocean in the spring, and migrated out of the estuary to the ocean in the fall. Differences in the salinity regime in the Columbia River Estuary from June to September may also have influenced crab distribution. From late May through early July 2002, river flows ranged between 300 and 400 Kcfs; in September, river flows ranged from 90 to 150 Kcfs. Avoidance of low salinity water at high river flows may have caused the 1+ crab to move from the shallower areas to the deeper and saltier waters of the channels.

The following projections, listed with entrainment source data in parentheses, represented worst-case losses (AEL at 2+) for the combination of both construction dredging increments: Flavel Bar (Desdemona September), Desdemona (Desdemona September), Upper Sands (Upper Sands), and Tongue Point (Upper Sands). Best-case losses were as follows: Desdemona (Desdemona June), Flavel Bar (Upper Sands), Upper Sands (Upper Sands), Tongue Point (Miller Sands). It should be noted that although Desdemona June total entrainment values are higher, Desdemona September data have a greater source of impact on projected adult losses because samples were dominated by older crabs. For locations not sampled in 2002 (Flavel Bar and Tongue Point) entrainment rates for sampled locations downriver yielded the highest projected losses (worst case); conversely, entrainment rates from adjacent upriver locations yielded lowest projected losses (best case).

Projections for crab entrainment during the Channel Improvement Project have some assumptions that need to be noted. First, the projections were based on currently planned dredge volumes. These projections will need to be changed if the dredged volumes at the planned locations are modified; actual impacts will depend on the volumes finally dredged during the project. Second, crab entrainment data were not collected at Flavel Bar and Tongue Point, and we attempted to bound the projected range of likely impacts by using data collected in adjacent areas. As a result, projections for Flavel Bar are probably overestimated by using data from Desdemona Shoals and underestimated by using data from Upper Sands. We recommend a high priority be given to obtaining entrainment data from upriver areas (Flavel Bar and Tongue Point) not sampled during 2002. Third, location specific entrainment data encompassed a range of effort that was generally dictated by the dredge schedule. In general, the coefficient of variation (CV) falls as sampling effort (e.g., number of sampling days) increases. More sampling days at each upriver location would narrow the confidence limits associated with entrainment projections. Finally, the estimates made in this paper are constrained by many of the same assumptions noted by Armstrong et al. (1987) and Wainwright et al. (1992), for estimates of crab size-at-age, mortality, survival, and exploitation rates.

The crab loss projections in this paper fall within the range reported by previous authors for Grays Harbor (Armstrong et al. 1987, Wainwright et al. 1992). Our estimates reflect a loss of approximately 38,811 to 281,528 age 2+ crabs for the combined construction increments, and of 25,612 to 56,840 age 2+ crabs for annual maintenance under the Proposed Plan (43' Channel). These estimates correspond to fishery losses of approximately 7,252 to 44,342 age 3+ male crabs for the combined construction increments, and of 4,035 to 8,953 age 3+ male crabs for annual maintenance under the Proposed Plan. Worst-case projected fishery losses represent about 1% of the annual crab landings for the Washington and Oregon region around the Columbia River (5.3 million crabs from 1991 to 2001). In the hypothetical Grays Harbor confined disposal scenario presented by Wainwright et al. (1992), estimated losses of age 2+ crabs ranged from 166,000 to 587,000 crabs. Wainwright et al.'s (1992) estimates correspond to fishery losses from 37,000 to 134,000 age 3+ male crabs, which represented 1% to 4% of the average annual catch by the Washington coast fishery.

The scientific literature, scenario analyses, and the summer 2002 site-specific data on entrainment and salinity all indicate that bottom salinity influences crab distribution, especially at lower salinities. It is now clear from field measurements of entrainment rates and salinity during a period of low river flow (90-150 Kcfs) and high salinity intrusion that entrainment rates are zero where bottom salinity is less than 16 o/oo most of the time. This result is supported by physiological studies that indicate that Dungeness crab are stressed and become inactive at 16 o/oo. Also, McCabe et al. (1986) found no crab at stations with average bottom salinities of 3.5 and 8 o/oo (above RM18) and found crab only “infrequently” at stations with average bottom salinities of 15.9 (about RM14) and 20.2 (about RM12). The model for the influence of salinity on crab distribution and entrainment needs further development. The relationship of the 1+ crab to salinity appears to be more complex than that for the 2+ and older crabs, for which the regressions between the logarithm of crab entrainment rate and the percentage of salinity observations below 16 o/oo were significant and explained a high degree (91%) of the variation.

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ACKNOWLEDGEMENTS

This study would not have been possible without the assistance and sacrifice of a number of individuals. First of all, we would like to gratefully acknowledge the contributions of Captain Nyberg, Captain Henry, and each crew member aboard the USACE Dredge *Essayons*. Their accommodating attitude, gracious hospitality, and innovative problem solving provided a safe, enjoyable working atmosphere that enabled us meet all of our project goals. We would also like to thank the Battelle field crew: Mike Anderson, Gary Dennis, Heida Diefenderfer, Nathan Evans, Nancy Kohn, Lohna O'Rourke, John Southard, and Jeff Ward, who were adaptable to an ever-changing dredge schedule and often worked under difficult field conditions. The quality of this data is a tribute to their hard work and dedication. We would also like to thank Tim Burge (USACE engineer) for assistance in conducting flow velocity measurements, as well as Jim Calnon (USACE engineer), Rachel Gumpenberger (USACE engineer), and Calvin Hsieh (USACE engineer) for sampling efforts during the June field trials. This work was supported by the USACE Portland District. Mr. Kim Larson was the USACE Technical Representative; Ms. Laura Hicks was the USACE Project Manager for the Channel Improvement Project.

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2.0 FIGURES

Figure 1. Crab Density (crab/ha) as a Function of Bottom Salinity. Plotted from Data of Stevens and Armstrong (1984). Note logarithmic scale.

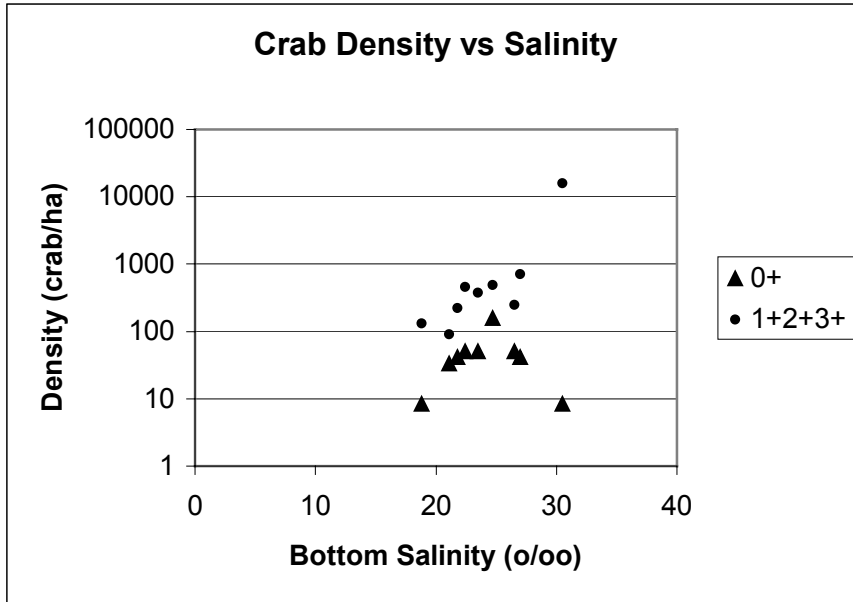


Figure 2. The Relationship Between Crab Density and Bottom Salinity from Regression Equation. Based on Data of Stevens and Armstrong (1984).

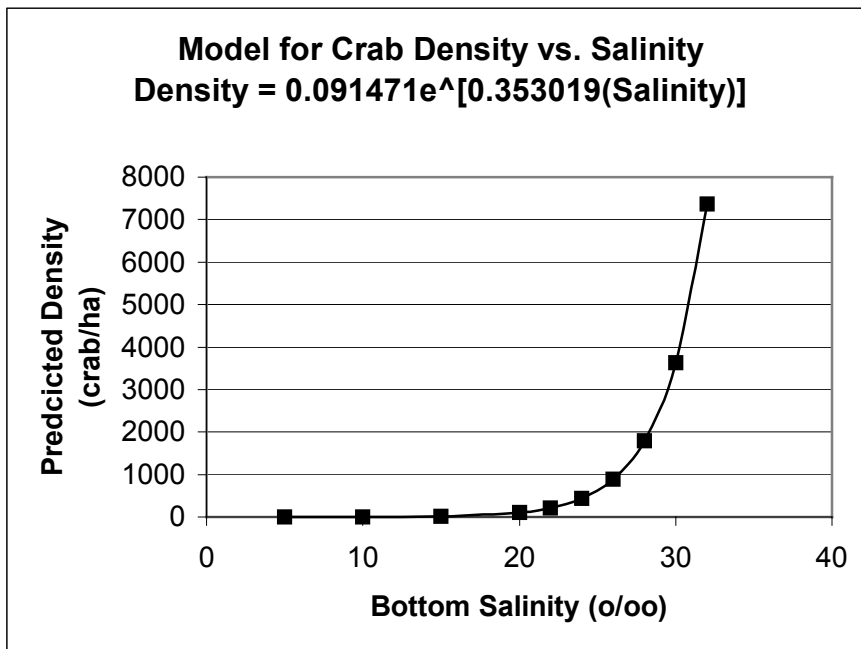


Figure 3. River Flow in the Columbia River Estimated by Combining Flow Measurements at Bonneville Dam and the Willamette River.

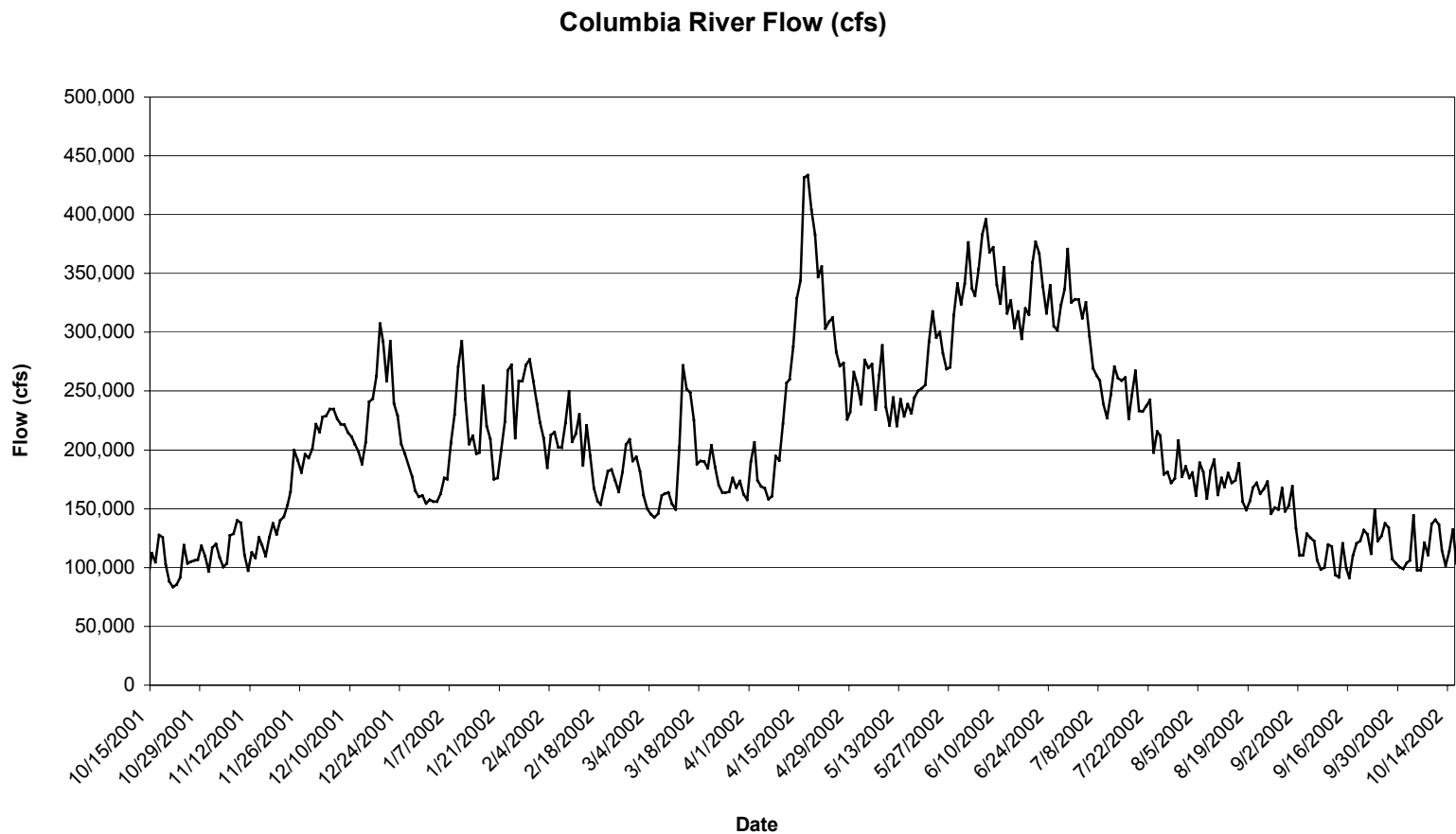


Figure 4. Bottom Salinity from CORIE Mean Salinity Profile Predicted by ELCIRC Model for May 21 and September 1, 2002.

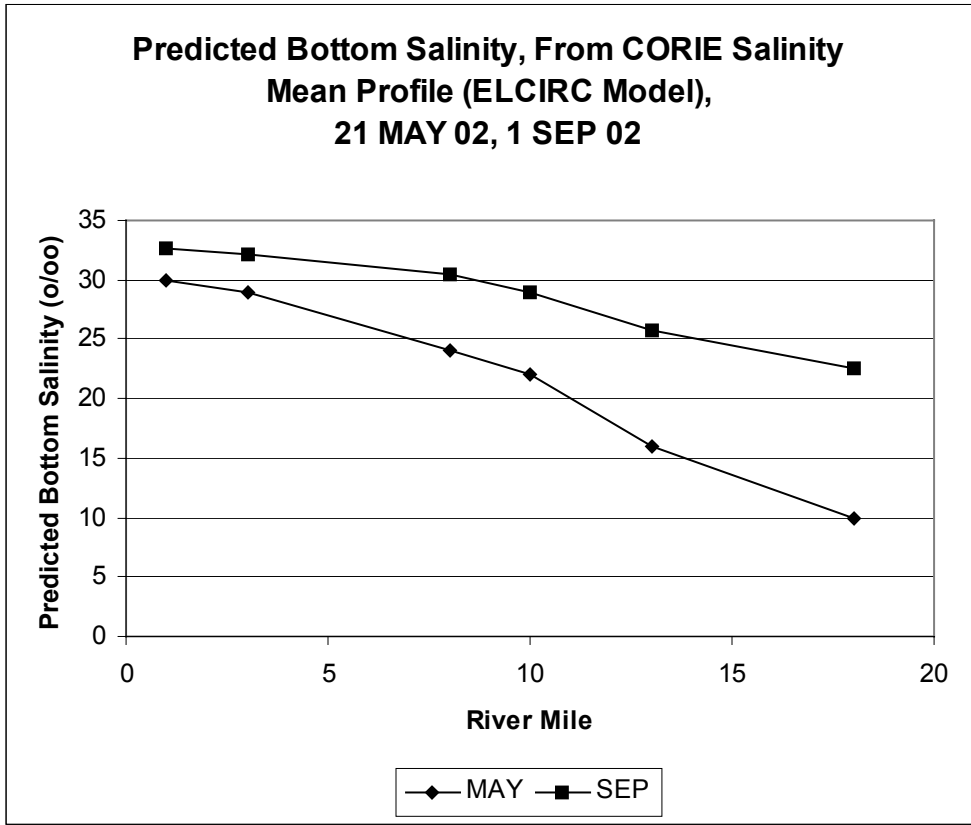


Figure 5. The Entrainment Function from the Grays Harbor Dredge Impact Model with Data from Columbia River Plotted on Same Scale

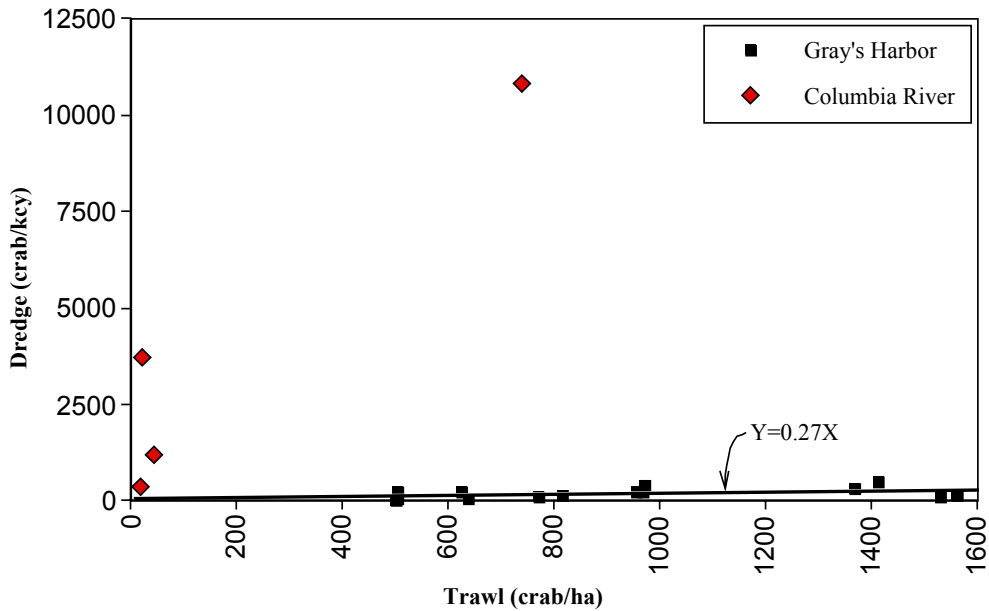


Figure 6. The Structure of a Modified Model for Estimating Entrainment Impacts on Dungeness Crab.

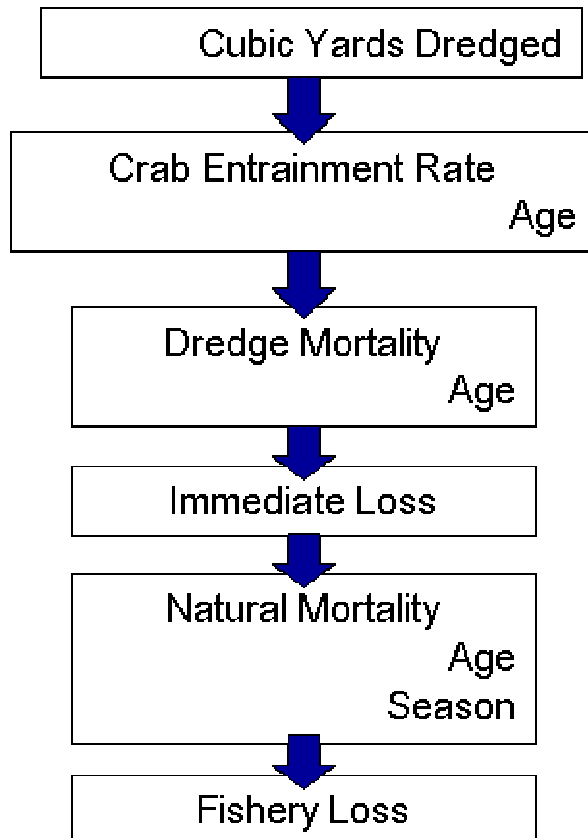


Figure 7. Map of the Study Area with Sampling Areas, Summer 2002.

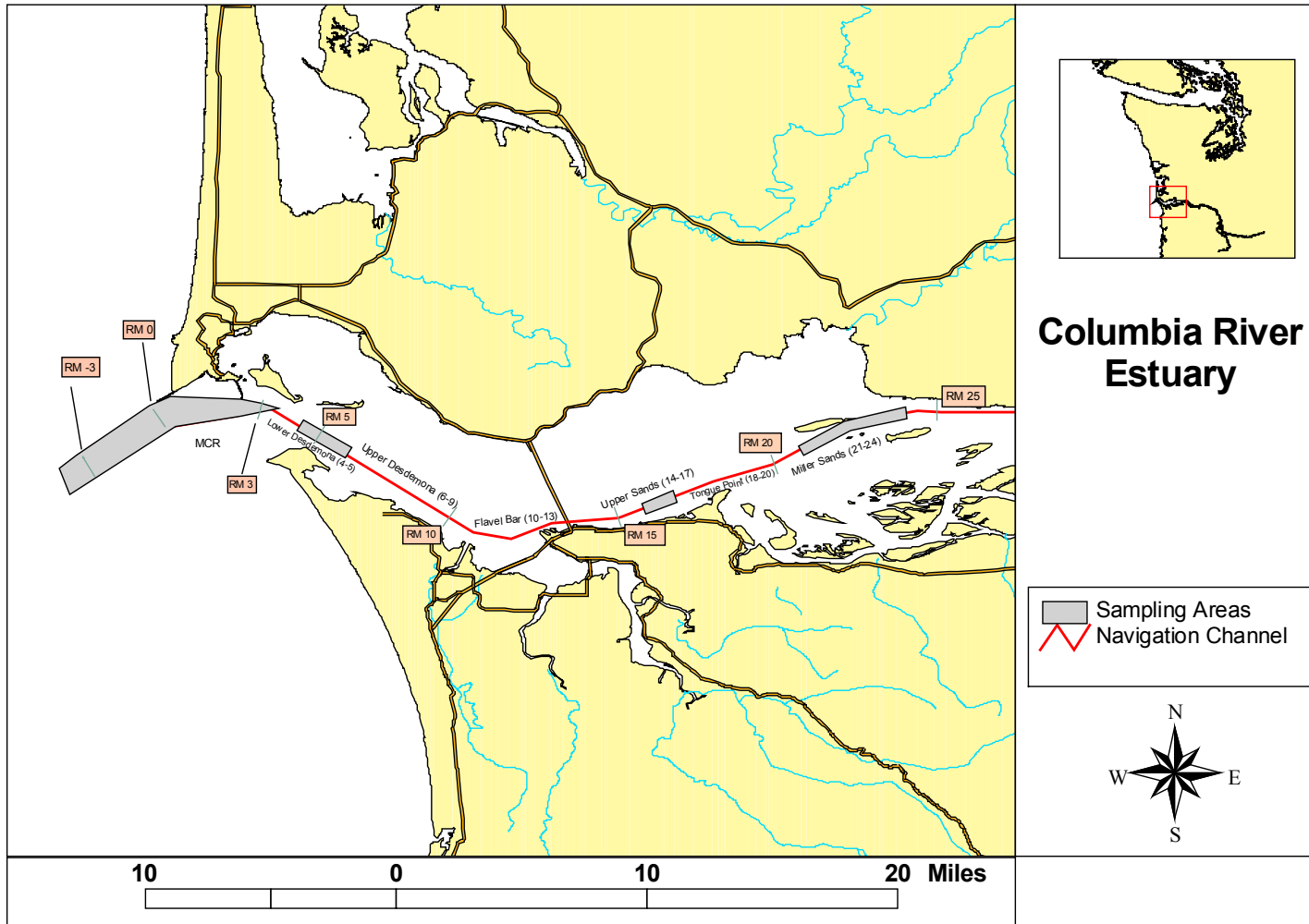


Figure 8. Diagram of the Piping and Valving on the Corps' Dredge Essayons, Summer 2002.

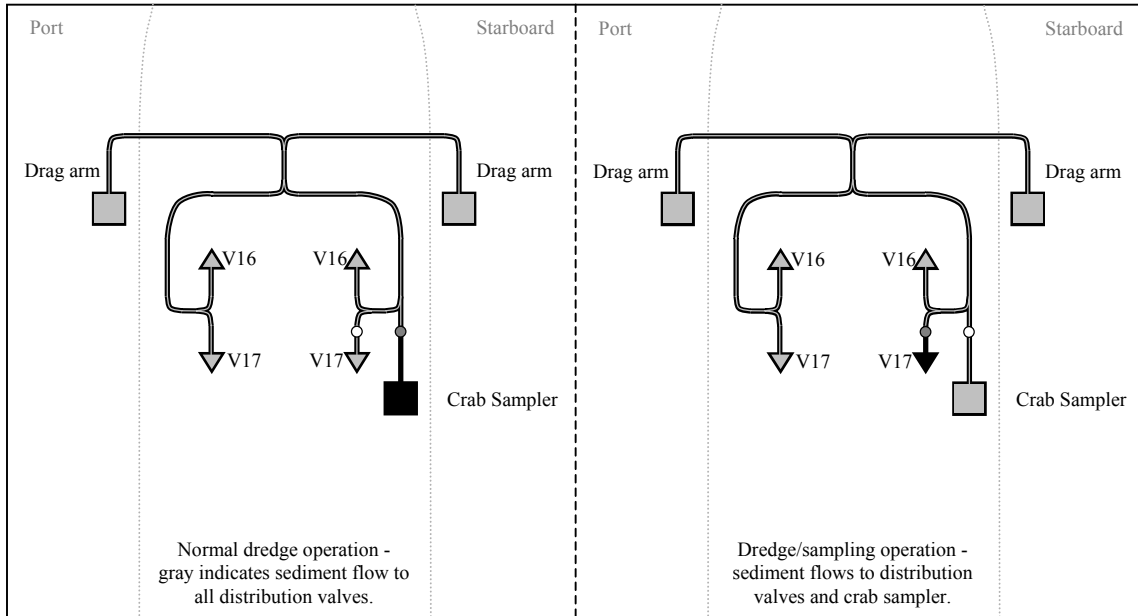


Figure 9. Predicted Crab Density for Six Salinity Intrusion Conditions. From Jay and Smith (1990).

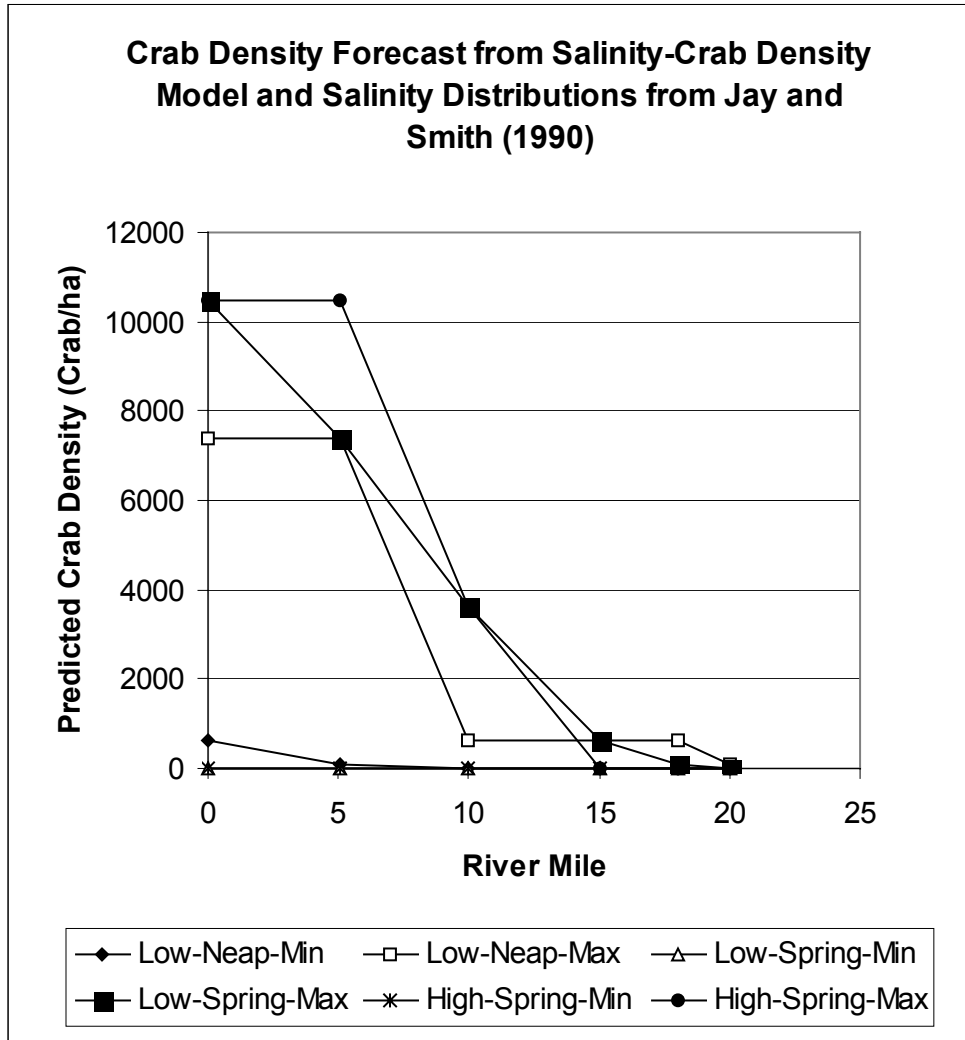


Figure 10. Predicted Crab Density for the Median Low Flow Salinity Intrusion.
From Jay and Smith (1990).

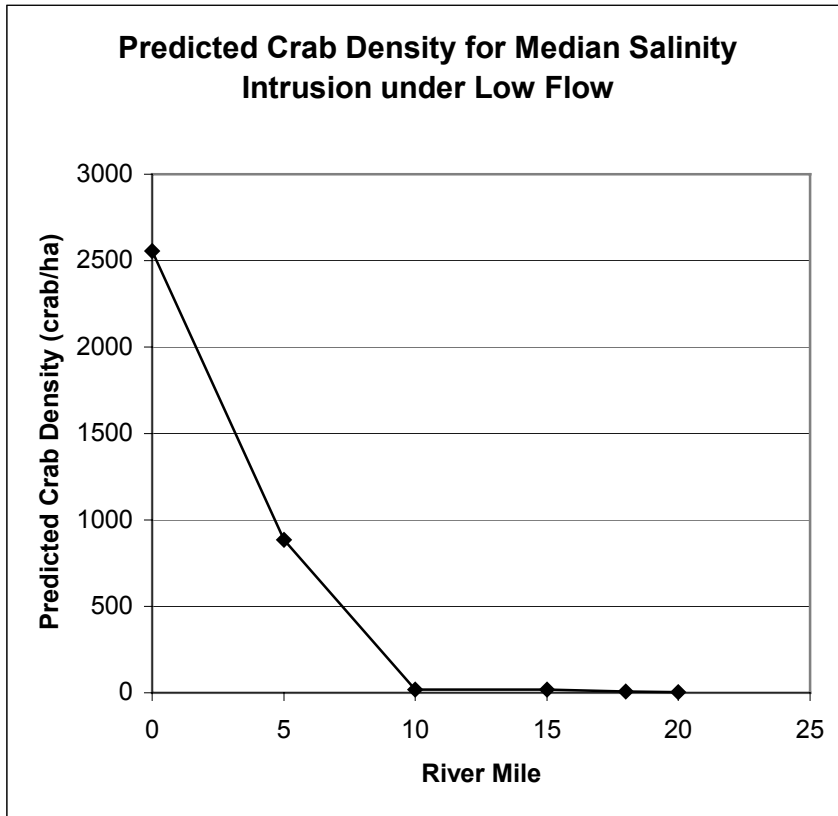
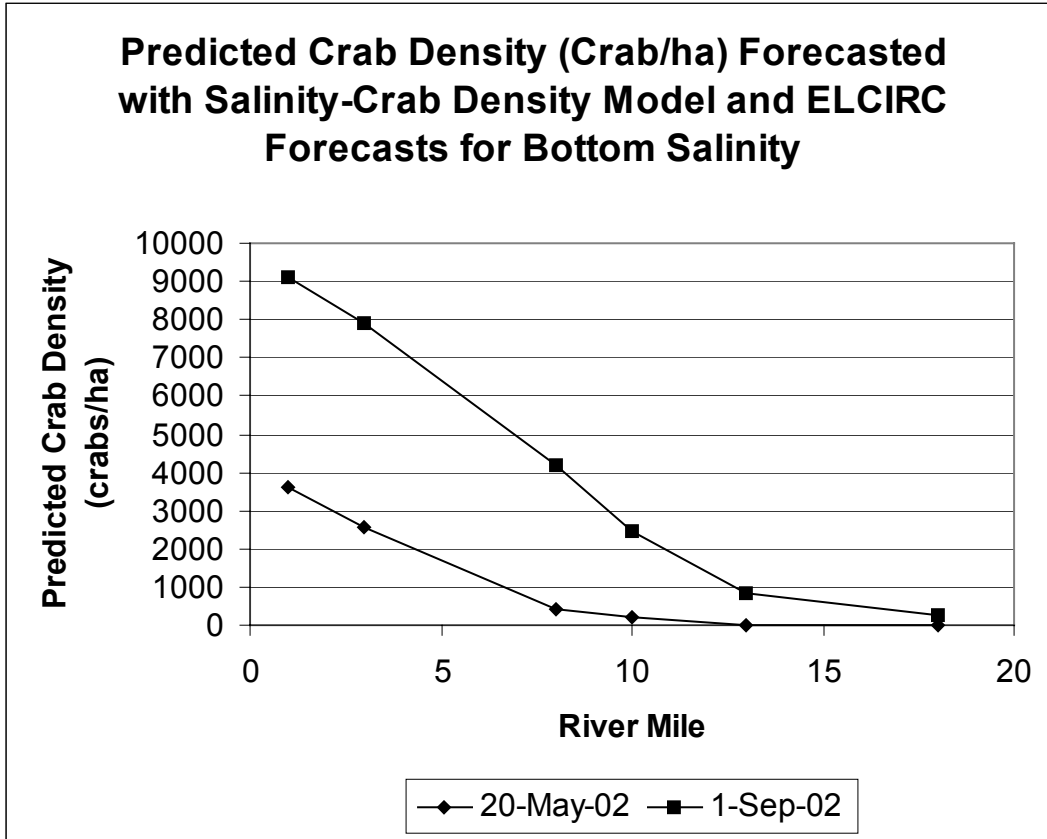


Figure 11. Predicted Crab Density Forecasted with the Salinity Crab Density Model and the ELCIRC Forecasts for Bottom Salinity.



3.0 TABLES

Table 1. 1+ Crab Densities by Habitat Type. From Rooper et al. (2002). Densities interpreted from graphs in Rooper et al. (2002) and other data taken from tables in Rooper et al. (2002).

Bay	n	Mean 1+ Density (crab/ha)		
		Lower Main Channel	Lower Side Channel	Upper Estuary
Grays Harbor	9	483	1722	228
Willapa Bay	9	270	772	216
Yaquina Bay	3	630	830	296
Coos Bay	3	571	1300	695
Mean		489	1156	359
Mean Salinity (o/oo)		28.5	26.1	25.1
Tide Flat (%)		20.7	53	40.1

Table 2. Isohaline Positions in the Columbia River as a Function of River Flow and Tidal Regime. Data taken from Graphs in Jay and Smith (1990).

Conditions			Isohaline Position (River Mile)				
Flow	Tide	Max/Min	30 o/oo	25 o/oo	20 o/oo	15 o/oo	10 o/oo
Low Flow	Neap	Minimum	0	3.8	5.0	5.4	6.5
Low Flow	Neap	Maximum	7.3	18.3	23.8	24.6	25.0
Low Flow	Spring	Minimum	0	0	0	5.4	7.1
Low Flow	Spring	Maximum	11.1	14.3	17.1	18.9	20.4
High Flow	Spring	Minimum	0	0	0	0	0
High Flow	Spring	Maximum	9.6	11.8	12.9	14.6	15.0

Table 3. Salinity Intrusion as a Function of River Mile in the Columbia River. Data taken from Graphs in Jay and Smith (1990).

Conditions			Within Isohaline at Position				
Flow	Tide	Max/Min	RM5	RM10	RM15	RM18	RM20
Low Flow	Neap	Minimum	20.0	5.0	5.0	5.0	5.0
Low Flow	Neap	Maximum	32.0	25.0	25.0	25.0	20.0
Low Flow	Spring	Minimum	15.0	5.0	0.5	0.0	0.0
Low Flow	Spring	Maximum	32.0	30.0	25.0	20.0	15.0
High Flow	Spring	Minimum	0.0	0.0	0.0	0.0	0.0
High Flow	Spring	Maximum	33.0	30.0	10.0	0.0	0.0
Median of Low Flow			26.0	15.0	15.0	12.5	10.0

Table 4. Crab Density Determined by Scientific Trawling and Calculated from Dredge Entrainment. The data from Wainwright et al. (1990) are from Grays Harbor, where the trawl and entrainment observations were paired. The data from Larson (1993) are from the Columbia River and the observations were not paired.

Total Crab			0+			1+			
Wainwright et al. 1990			Larson (1993)			Larson (1993)			
Station	Crab Density (crab/ha)		Station	Crab Density (crab/ha)		Station	Crab Density (crab/ha)		
	by Trawl	by Dredge		by Trawl	by Dredge		by Trawl	by Dredge	
1	625	208	May-85	333	15,831	May-85	13	118	
1.5	1367	352	May-86	0	3004	May-86	31	210	
2	1530	148	May-87	1636	25764	May-87	37	288	
3	956	322	May-88	1758	No Data	May-88	32	No Data	
3.5	502	49	Jun-85	56848	35943	Jun-85	7	70	
Mean	1004	216	Jun-86	424	3894	Jun-86	71	183	
			Jun-87	576	8527	Jun-87	14	295	
			Jun-88	303	1822	Jun-88	9	96	
			Mean	7735	13541	Mean	27	180	
RATIO Dredge to Trawl			0.215	RATIO Dredge to Trawl		1.751	RATIO Dredge to Trawl		6.729

Table 5. Sampling Effort Associated with Various Locations of Crab Entrainment Sampling on the Dredge *Essayons* During Summer 2002.

Location	River Mile	Dates (2002)	Total Dredged Volume (cy)	Total Loads Dredged	Total Loads Sampled	Total Basket Samples
Desdemona Shoals	+4 to +7	11 to 15 JUN	186,737	33	17	169
Desdemona Shoals	+4 to +7	17 SEP	30,012	6	4	12
Upper Sands	+16	23 SEP	54,036	9	9	27
Miller Sands	+21 to +24	1 to 8 OCT	443,563	75	36	140
Mouth of Columbia River	-3 to +3	8 JUL to 15 OCT	2,763,119	489	214	643

Table 6. Coefficients of Variation of Different Rates of Basket Samples per Dredge Load. Based on Data of Larson (1993).

Basket Samples Per Load	CV	
	All Loads	1/2 Loads
2	0.139	0.221
3	0.113	0.187
4	0.098	0.167
5	0.088	0.154
6	0.08	0.144
7	0.074	0.137
8	0.07	0.131
9	0.066	0.127
10	0.062	0.123

Table 7. Coefficients of Variation of Different Rates of Basket Samples per Dredge Load. Based on Data from June 2002. Note: The column for 0+ crab uses all 17 loads of which only 5 detected 0+ age class; precision calculations based on only the loads with observed crabs yields a CV of 0.114 for 2 basket samples per load.

Basket Samples per Load	Age Class			
	0+	1+	2+	3+
1	0.185	0.064	0.151	0.268
2	0.149	0.049	0.103	0.24
3	0.135	0.043	0.086	0.23
4	0.127	0.04	0.076	0.224
5	0.122	0.038	0.07	0.221

Table 8. Projected Dredge Volumes for Future Construction Dredging (to 40' and from 40' to 43') Associated With the Columbia River Channel Improvement Project.

Dredging to 40'			Dredging from 40' to 43'		
River Mile	Location	Volume (cy)	River Mile	Location	Volume (cy)
4	Lower Desdem.	94,688	4	Lower Desdem.	222,412
5		196,724	5		353,916
6	Upper Desdem	66,193	6	Upper Desdem	0
7		1,039	7		0
8		52,398	8		8,742
9		62,851	9		8,742
10	Flavel Bar	329,296	10	Flavel Bar	49,732
11		535,074	11		298,900
12		239,608	12		121,292
13		65,743	13		72,425
14	Upper Sands	171,432	14	Upper Sands	54,585
15		271,842	15		51,945
16		306,717	16		47,557
17		108,631	17		0
18	Tongue Point	174,113	18	Tongue Point	14,775
19		162,864	19		6,976
20		127,219	20		13,283
Total		2,966,432	Total		1,325,282

Summary of Planned Construction Volumes

Location	To 40'	From 40' to 43'	Combined
MCR	ND	ND	ND = No Data
Desdemona (Upper and Lower)	473,893	593,812	1,067,705
Flavel Bar	1,169,721	542,349	1,712,070
Upper Sands	858,622	154,087	1,012,709
Tongue Pt	464,196	35,034	499,230
Miller Sands	ND	ND	ND

Table 9. Projected Volumes During Year 1 and Year 20 Maintenance Dredging Associated with 40-foot Channel Maintenance (No Action Alternative) and the 43-foot Alternative (Proposed Plan).

Location	40-foot Channel Maintenance (No Action Alternative)		43-foot Alternative Maintenance (Proposed Plan)	
	Year 1	Year 20	Year 1	Year 20
Desdemona	40,000	40,000	60,000	40,000
Flavel Bar	400,000	210,000	500,000	210,000
Upper Sands	50,000	50,000	100,000	100,000
Tonque Point	270,000	270,000	330,000	330,000

Table 10. Entrainment Rates from Direct Measurements in Summer 2002.

Area	Age Class				
	0+	1+	2+	3+	All
Desdemona June	0.005	0.193	0.024	0.001	0.224
Desdemona Sept	0.000	0.022	0.065	0.033	0.120
Upper Sands	0.010	0.010	0.000	0.000	0.021
Miller Sands	0.000	0.000	0.000	0.000	0.000

Table 11. Summary of Entrainment Rates (R), Entrainment (E), Adult Equivalent Loss (AEL), and Loss to Fishery (LF) with 95% Confidence Intervals (CI) for the Dredged Volumes Accomplished During the Summer of 2002.

Location	R	E	95%CI	AEL 2+	95%CI	AEL 3+	95%CI	LF	95%CI
Desdemona Jun	0.2236	41758.8	+4099.5	6314.1	+911.9	2841.3	+410.4	1193.9	+189.9
Desdemona Sep	0.1195	3586.2	+2068.7	3023.3	+1200.1	1360.5	+540.1	476.2	+189.0
Upper Sands	0.0205	1109.5	+1537.7	53.71	+103.5	24.2	+46.6	8.5	+16.3
Miller Sands	0.0000	0.00	n/a	0.00	n/a	0.00	n/a	0.00	n/a

Table 12. Contribution by Age Class to Adult Equivalent Loss (AEL) by Male (M) and Female (F) Crab from Summer 2002 Sampling.

Location	Age Class	Sex	Dredged Volume cubic yds	Contribution to AEL by age class				
				0+	1+	2+	3+	Total
Desd June	2+	M	186737	1	1732	1899	158	3790
		F		1	1732	633	158	2524
Desd June	3+	M	186737	0	780	855	71	1706
		F		0	780	285	71	1136
Desd Sep	2+	M	30012	0	31	546	934	1512
		F		0	31	546	934	1512
Desd Sep	3+	M	30012	0	14	246	421	680
		F		0	14	246	421	680
Upper Sands	2+	M	54036	0	26	0	0	27
		F		0	26	0	0	27
Upper Sands	3+	M	54036	0	12	0	0	12
		F		0	12	0	0	12
Miller Sands	2+	M	443563	0	0	0	0	0
		F		0	0	0	0	0
Miller Sands	3+	M	443563	0	0	0	0	0
		F		0	0	0	0	0

Table 13. Crab AEL and LF Projected for Construction Dredging to 40’.

			AEL	95% CI	Loss to Fishery	95% CI
Location	Age Class	Sex	Total		Total	
Desd June	2+	M	12,052	<u>+1,741</u>	3,796	<u>+603</u>
		F	8,026	<u>+592</u>		
Desd June	3+	M	5,423	<u>+783</u>	3,796	<u>+603</u>
		F	3,612	<u>+522</u>		
Desd Sep	2+	M	29,909	<u>+11,871</u>	9,422	<u>+3,739</u>
		F	29,909	<u>+11,871</u>		
Desd Sep	3+	M	13,459	<u>+5,342</u>	9,422	<u>+3,739</u>
		F	13,459	<u>+5,342</u>		
Flavel Bar*	2+	M	11,008	<u>+1,590</u>	3,467	<u>+3,467</u>
		F	7,331	<u>+1,059</u>		
Flavel Bar*	3+	M	4,953	<u>+716</u>	3,467	<u>+3,467</u>
		F	3,299	<u>+477</u>		
Flavel Bar**	2+	M	27,317	<u>+10,842</u>	8,605	<u>+3,415</u>
		F	27,317	<u>+10,842</u>		
Flavel Bar**	3+	M	12,293	<u>+4,879</u>	8,605	<u>+3,415</u>
		F	12,293	<u>+4,879</u>		
Flavel Bar***	2+	M	270	<u>+519</u>	85	<u>+164</u>
		F	270	<u>+519</u>		
Flavel Bar***	3+	M	121	<u>+234</u>	85	<u>+164</u>
		F	121	<u>+234</u>		
Upper Sands	2+	M	77	<u>+148</u>	24	<u>+46</u>
		F	77	<u>+148</u>		
Upper Sands	3+	M	34	<u>+66</u>	24	<u>+46</u>
		F	34	<u>+66</u>		
Tongue Pt!	2+	M	17	<u>+34</u>	6	<u>+11</u>
		F	17	<u>+34</u>		
Tongue Pt!	3+	M	8	<u>+15</u>	6	<u>+11</u>
		F	8	<u>+15</u>		
Tongue Pt!!	2+	M	0	n/a	0	n/a
		F	0	n/a		
Tongue Pt!!	3+	M	0	n/a	0	n/a
		F	0	n/a		
Miller Sands	2+	M	0	n/a	0	n/a
		F	0	n/a		
Miller Sands	3+	M	0	n/a	0	n/a
		F	0	n/a		

* based on Desdemona JUN entrainment rates
** based on Desdemona SEP entrainment rates
*** based on Upper Sands entrainment rates
! based on Upper Sands entrainment rates
!! based on Miller Sands entrainment rates

Table 14. Crab AEL and LF Projected for Construction Dredging from 40' to 43'.

			AEL	95% CI	Loss to Fishery	95% CI
Location	Age Class	Sex	Total		Total	
Desd June	2+	M	9,618	+1,389	3,030	+482
		F	6,405	+925		
Desd June	3+	M	4,328	+625	3,030	+482
		F	2,882	+416		
Desd Sep	2+	M	23,869	+9,474	7,519	+2,984
		F	23,869	+9,474		
Desd Sep	3+	M	10,741	+4,263	7,519	+2,984
		F	10,741	+4,263		
Flavel Bar*	2+	M	23,741	+3,429	7,478	+1,189
		F	15,811	+2,284		
Flavel Bar*	3+	M	10,683	+1,543	7,478	+1,189
		F	7,115	+1,028		
Flavel Bar**	2+	M	58,917	+23,384	18,559	+7,366
		F	58,917	+23,384		
Flavel Bar**	3+	M	26,513	+10,523	18,559	+7,366
		F	26,513	+10,523		
Flavel Bar***	2+	M	581	+1,120	183	+353
		F	581	+1,120		
Flavel Bar***	3+	M	262	+504	183	+353
		F	262	+504		
Upper Sands	2+	M	427	+822	134	+259
		F	427	+822		
Upper Sands	3+	M	192	+370	134	+259
		F	192	+370		
Tongue Pt!	2+	M	231	+444	73	+140
		F	231	+444		
Tongue Pt!	3+	M	104	+200	73	+140
		F	104	+200		
Tongue Pt!!	2+	M	0	n/a	0	n/a
		F	0	n/a		
Tongue Pt!!	3+	M	0	n/a	0	n/a
		F	0	n/a		
Miller Sands	2+	M	0	n/a	0	n/a
		F	0	n/a		
Miller Sands	3+	M	0	n/a	0	n/a
		F	0	n/a		

* based on Desdemona JUN entrainment rates
** based on Desdemona SEP entrainment rates
*** based on Upper Sands entrainment rates
! based on Upper Sands entrainment rates
!! based on Miller Sands entrainment rates

Table 15. Summary of AEL at 2+ and Losses to Fishery For Construction Dredging Under Worst- and Best-Case Assumptions.

Project Location	AEL at 2+ Under Assumptions		Loss to Fishery Under Assumptions	
	Worst-case	Best-case	Worst-case	Best-case
Dredging to 40'				
Desdemona	59,818	20,078	9,422	3,796
Flavel	54,634	540	8,605	85
Upper Sands	154	154	24	24
Tongue Point	34	0	6	0
Total	114,640	20,772	18,057	3,905
Dredging from 40' to 43'				
Desdemona	47,738	16,023	7,519	3,030
Flavel	117,834	1,162	18,559	183
Upper Sands	854	854	134	134
Tongue Point	462	0	73	0
Total	166,888	18,039	26,285	3,347
Total Dredging Volume				
OVERALL	281,528	38,811	44,342	7,252

Table 16. Summary of AEL at 2+ and Losses to Fishery For Maintenance Dredging in Year 1 and Year 20 Under Worst-Case Assumptions for Both the “No Action Alternative” and the Proposed Project.

Project Location	AEL at 2+ Under Assumptions		Loss to Fishery Under Assumptions	
	Year 1	Year 20	Year 1	Year 20
40-foot Channel Maintenance (No Action Alternative)				
Desdemona	4,030	4,030	635	635
Flavel	40,295	21,155	6,346	3,332
Upper Sands	50	50	8	8
Tongue Point	268	268	42	42
Total	44,643	25,503	7,031	4,017
43-foot Alternative Maintenance (Proposed Project)				
Desdemona	6,044	4,030	952	635
Flavel	50,369	21,155	7,933	3,332
Upper Sands	99	99	16	16
Tongue Point	328	328	52	52
Total	56,840	25,612	8,953	4,035

Table 17. Entrainment Rates by Location and the Percentage of Salinity Observations More Than 32 o/oo and Less Than 16 o/oo. Note: 0.001 has been added to rates to enable logarithmic transformation before regression.

Location	Entrainment Rate (crab/cy)			% of Salinity Observations	
	Age 1+	Age 2+3+	All Ages	>32 o/oo	<16 o/oo
Desdemona JUN	0.193	0.025	0.224	38	16
Desdemona SEP	0.022	0.098	0.121	83	0
Upper Sands	0.01	0.001	0.021	0	67
Miller Sands	0.001	0.001	0.001	0	100
MCR	0.014	0.042	0.057	96	1

Table 18. Results of Regression Analysis Between the Natural Logarithm of the Entrainment Rates and Percentage of Salinity Observations Above 32 o/oo and Below 16 o/oo. Regressions with asterisk are significant.

Salinity	Entrainment Rate		
	All Ages	Age 1+	Age 2+ & 3+
%>32 o/oo	p=0.25	p=0.51	p=0.02*
			(r ² =0.81)
%<16 o/oo	p=0.03*	p=0.15	p=0.01*
	(r ² =0.86)		(r ² =0.91)