Impacts of Shoreline Armoring on Sediment Dynamics

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Abstract. The shores of Puget Sound rapidly are being hardened and covered with artificial structures. Although shoreline armoring often succeeds in protecting upland investments, shoreline armoring activities are hypothesized to represent a significant source of nearshore morphodynamic and marine habitat modification in Puget Sound. Shoreline armoring is believed to affect physical processes in many ways, primarily by causing beach narrowing, sediment coarsening, and a decrease in the natural sediment supply from eroding bluffs. Shoreline armoring also is thought to affect biological processes through loss of upper intertidal habitat, changes in sediment composition, and decreased organic input. However, it has not been conclusively confirmed in the field or the laboratory whether currents and sediment transport rates will increase or decrease in front of a hardened shoreline, as compared to a non-armored section of beach, and whether the sedimentary environment will be significantly modified. The effect of seawalls on beaches has been found to be most sensitive to the position of the seawall within the surf zone, the beach slope, and the reflection coefficient. This paper will review various studies exploring seawall impacts on sediment dynamics and suggest pilot investigations specific to the Puget Sound consisting of beach monitoring, field experiments, and modeling efforts.

Introduction

The effect of seawalls on beaches has been a topic of considerable research and controversy for many years, and recent reviews of the available literature (Kraus, 1987; Griggs and Tait, 1990; Kraus and McDougal, 1996; Coyle and Dethier, 2010) have demonstrated the need for still more study. Beaches have been reputed to respond to wave-seawall interactions in many ways, including; the formation of scour troughs, beach lowering, end scour, up-coast accretion, down-coast erosion, far down-coast shoals, reflection bars, and delayed post-storm recovery. Processes identified as having contributed to these possible responses include those such as sediment impoundment (groin effect), removal of upland sand from the sediment budget, wave reflection (fig. 1), acceleration of longshore currents, and increased sediment mobilization. Controls on how these processes affect beach change also have been discussed: long term shoreline change (passive or background erosion), storm events (active erosion), position of the seawall relative to the surf zone, width of the surf zone, sediment supply, and specific characteristics of waves and the seawall.

Figure 1. Seawalls impact nearshore hydrodynamics in many ways, including wave reflection. Photo Credit Carl Schoch (Homer, Alaska).

Confusion and disagreement in the literature is compounded by the lack of sufficient field data and confounding results from physical and theoretical models. In this (non-exhaustive) review we highlight a variety of recent efforts aimed at understanding the impacts of seawalls on sediment dynamics. We then offer a suggestion as to why such confusion remains and suggest some areas where studies specific to the Puget Sound can shed light on this difficult problem.

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Classifying the Problem

It generally is accepted that on beaches experiencing **passive erosion** (for example, beaches eroding because of relative sea-level rise) the beach fronting a seawall will eventually disappear. As an example, the armoring of shorelines in Oahu, Hawaii, has been quantitatively shown to cause narrowing and the loss of sandy beaches over an approximately 50- year period on a coast experiencing 1.55 mm/yr of relative sea-level rise (fig. 2; Fletcher and others, 1997). In contrast, three long-term field studies have documented seawall-backed beaches experiencing no significant negative impacts. These studies, in California (Griggs and others, 1994), Oregon (Hearon and others, 1996), and Virginia (Jones and Basco, 1996), each extend over time scales on the order of a decade. No measurable or significant differences between profiles for seawall-backed and non-armored beaches were found in these studies, suggesting little long-term effect of seawalls on the beaches. Because these studies spanned periods of only about a decade, however, sea-level rise, and therefore passive erosion, was relatively unimportant. These studies were assessing the impacts of seawalls on beaches that intermittently were experiencing **active erosion**. The confusion, and sometimes controversy, is about the impacts of seawalls on beaches during episodes of active erosion.

The aforementioned results are in part attributable to the position of the walls relative to mean sea level and the frequency and intensity with which they are impacted by waves. In the California and Oregon studies, the walls were impacted by waves only during the largest winter storms. Weggel (1988) suggested a classification of seawall types based on the seawall's position on the beach and the water depth at the toe of the structure (table 1). The beaches in the Oregon and California field studies would be classified as Type I to Type III, depending on the season and storm condition, whereas the seawalls studied in Virginia can be classified as Type III to Type IV, depending on season and location. In this context, the Weggel (1988) classification helps to explain why the Oregon and California study sites experienced few decadal scale impacts as a result of armoring but sheds little light on the minor impacts experienced in the Virginia study. Data on the Oahu study sites are insufficient to enable their classification (Fletcher and others, 1997).

Table 1. Weggel's Seawall Classification.

Type	Location of Seawall
I	Landward of maximum storm runup – never impacted by nearshore hydrodynamics at present sea level stage
II	Above the still water line associated with maximum storm surge but below the level of the maximum runup
III	Above Mean High Water and below the still water line of storm surge
IV	Within the normal tide range; base is submerged at high water
V	Seaward of MLLW; base is always submerged; subjected to breaking or broken waves
VI	So far seaward that incident waves do not break on or seaward

Figure 2. Example of the impact of seawalls on beaches under conditions of 'passive' erosion. Photo Credit Chip Fletcher (Hawaii).

Recent Studies on the Impact of Seawalls

Cross-Shore Processes

A recent study developed a modified version of the cross-shore profile model SBEACH, which explicitly includes wave reflection from the seawall and its affect on wave breaking and setup (McDougal and others, 1996). This study yielded two surprising results. The first is that the beach change predictions including reflected waves were not substantially different from those neglecting reflection (that is, the standard SBEACH model with a no transport condition at the location of the seawall). The second was that a large scour trench did not always develop at the toe of the seawall, even for very energetic waves. These numerical results were confirmed in the 'large-scale' model tests conducted as a component of the SUPERTANK experiments (Kraus and others, 1992). The agreement of these two-dimensional numerical and physical models indicates that alongshore processes may be significant in event-scale seawall related effects (Kraus and McDougal, 1996). Unfortunately, there is much less understanding of the important alongshore processes in front of seawalls.

It should be noted, however, that in a recent 'medium-scale' wave flume experiment, El-Bisy (2007) physically simulated toe scour in front of seawalls and found that the scour depth increased with increasing distance of the seawall relative to the surf zone and with increasing wave steepness. Recent work, such as that by Lawrence and Chadwick (2005), who apply Boussinesq wave models to analyze the hydrodynamics of the partial standing wave in front of seawalls, are beginning to provide more rigorous insight on the processes and mechanisms involved in cross-shore sediment transport in front of seawalls, but significant work remains

Longshore Processes

Two recent studies provide the most detailed discussion of alongshore processes in front of seawalls available thus far, yet disagreement about the impact of seawalls remains. Rakha and Kamphuis (1997a and 1997b) developed a numerical model that includes the effect of a seawall on wave-transformation, wave-induced currents, and morphological evolution. Their numerical analyses, which were validated with small-scale physical model tests, suggested that seawalls had only a minor effect on the longshore current and beach profile evolution. In fact, the volume of erosion for beaches backed by seawalls was nearly the same as that for a beach without a seawall. Miles and others (2001) report on the first detailed field measurements of sediment transport processes in front of a seawall from an experiment on the southern coast of England. During the relatively low energy conditions measured, suspended sediment and longshore currents were observed to be stronger in front of a seawall than on an adjacent natural beach, resulting in a longshore sediment transport rate that was on the order of a magnitude greater in front of the wall. These results taken in combination suggest that it has not yet been (conclusively) confirmed in the field or the laboratory whether currents and sediment transport rates will increase or decrease in front of a hardened shoreline, as compared to a non-armored section of beach.

Ruggiero and McDougal (2001) developed a simple analytic model to estimate longshore currents and littoral transport on planar beaches backed by seawalls, the objective being to better understand the effect of seawalls on nearshore processes. The model is based on the depth- and time-averaged equations of motion in the nearshore, assuming no longshore gradients. Once the waves, incident and reflected, and the total water depth including setup are determined, the longshore equation of motion is used to calculate a mean longshore current. Once the longshore current in front of a seawall is known, an estimate of the longshore sediment transport profile is possible. Ruggiero and McDougal (2001) used a Bagnold-type energetics model (Bagnold, 1963), which simulates bed load and suspended load. The model assumes that the orbital wave motion mobilizes the sediment, wave power is expended maintaining the sediment in motion, and the presence of a mean current, regardless of how small, transports the sediment. In calculating the sediment transport, the same set of assumptions is employed as when determining the wave setup and the longshore current.

This model is an extension of the classical no seawall derivations of wave setup, longshore currents and longshore sediment transport on planar beaches (for example, Bowen and others, 1968; Bowen, 1969; Longuet Higgins, 1970a, 1970b; and McDougal and Hudspeth, 1983a, 1983b) and the standard assumptions are made. This model is developed for a beach backed by an infinite vertical seawall within the surf zone. The seawall must be located between the point of maximum setup on the beach face and the breaker line. Therefore, the model is valid for three of the six types of seawalls—Type-3, Type-4, and Type-5, described in Weggel's (1988) classification system—based on the seawall's location with respect to the shoreline (fig. 3). The model assumes shallow water, small angle of wave incidence, spilling breakers, and conservation of reflected wave energy flux. A partial standing wave develops in front of the seawall, causing modulations in the bottom shear stress, radiation stress, setup/setdown, longshore current, and longshore sediment transport (fig. 4). Modulations associated with the total water depth and bottom stress are relatively small and can be neglected. The modulation of the radiation stress is retained and forces longshore current and sediment transport profiles, which behave quite differently than no seawall formulations.

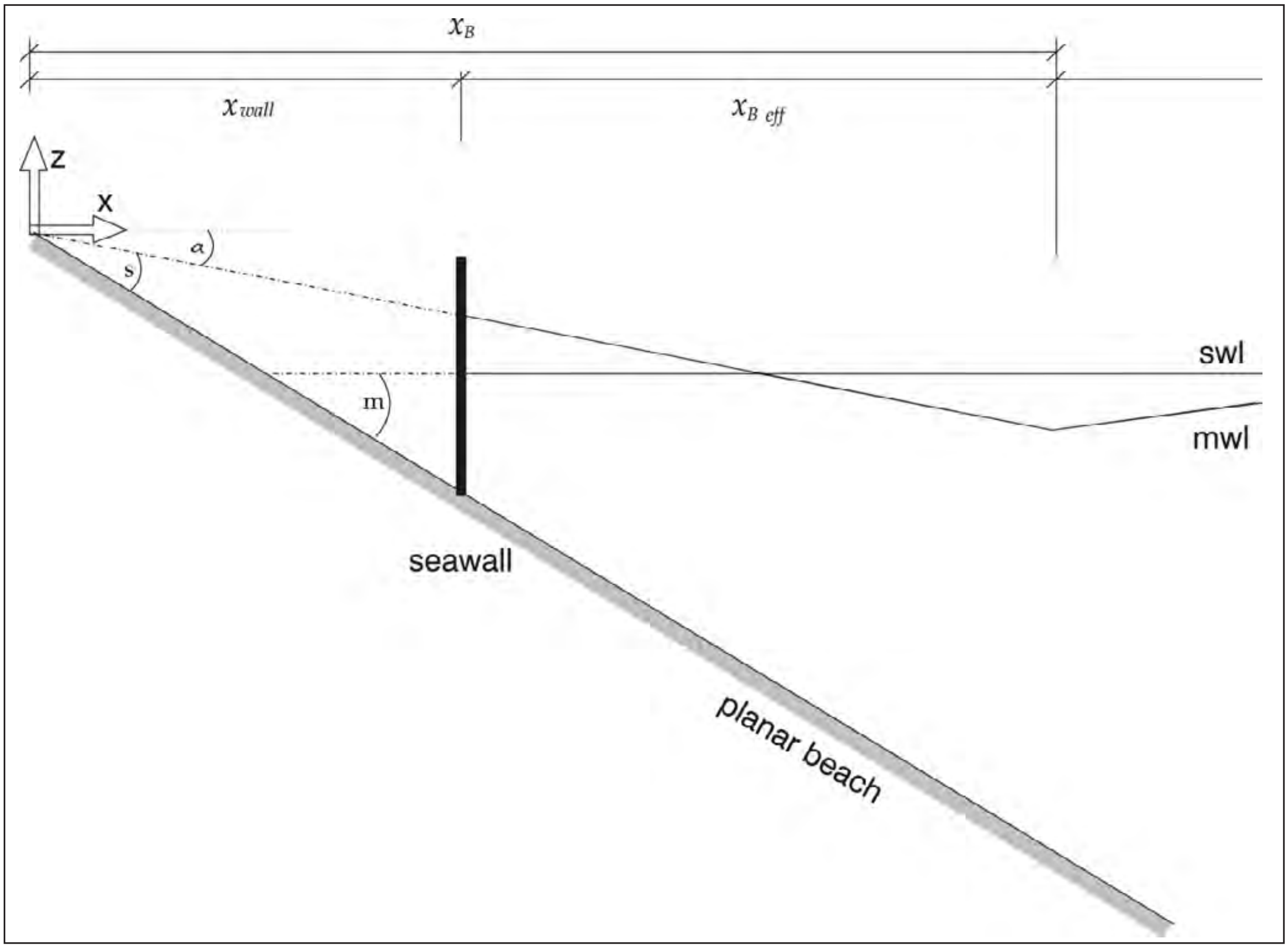

Figure 3. Profile view definition sketch of the analytical model of Ruggiero and McDougal (2001), where *m* is the planar beach slope, α is the slope of the wave setup, *s* is the total slope, x_{wall} is the cross-shore location of the seawall, x_B is the surf zone width, $x_{B\ eff}$ is the effective surf zone width with the seawall, *swl* is the still water line, and *mwl* is the mean water line accounting for wave setup/setdown.

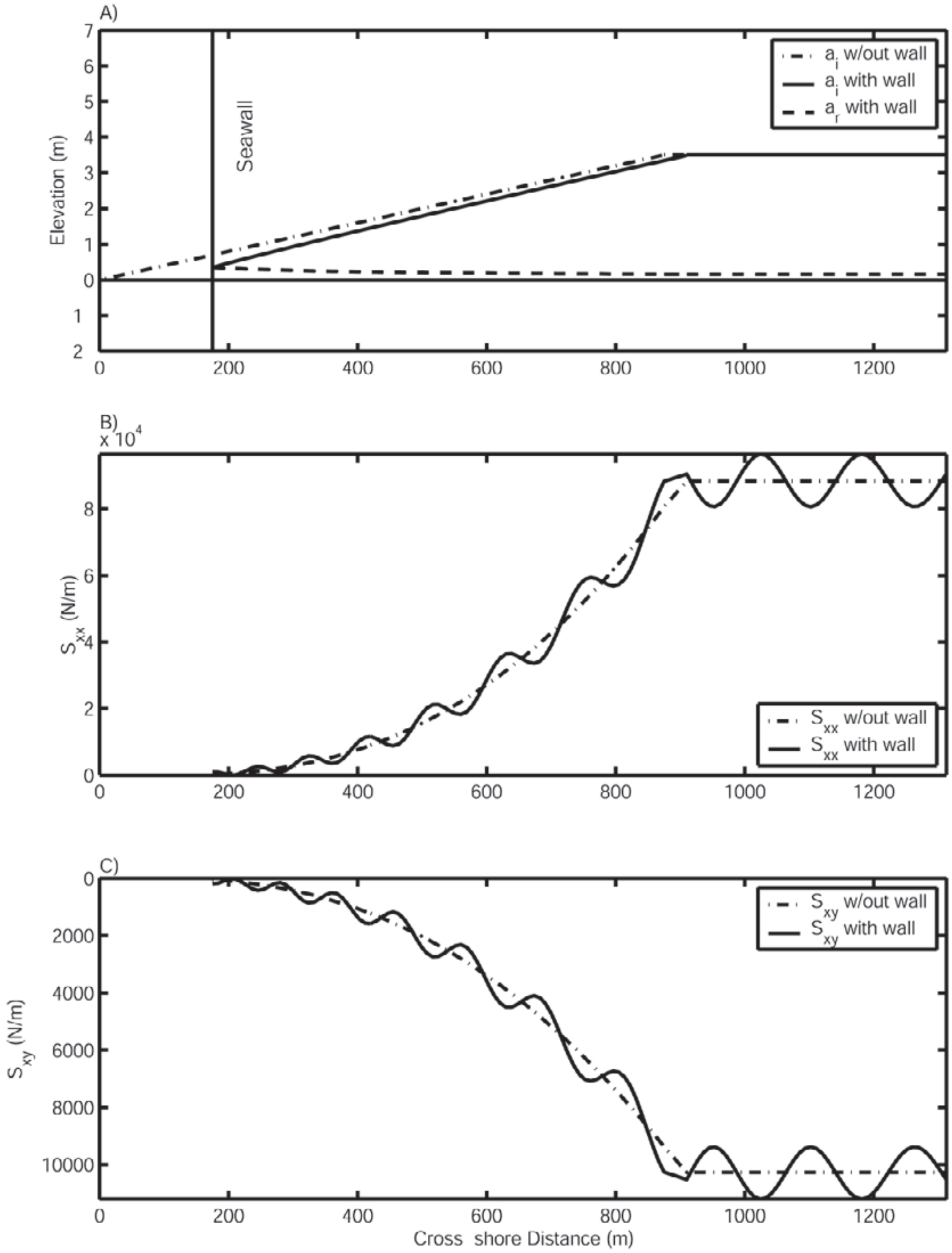

Figure 4. Cross-shore variation of (*A*) incident, a_i, and reflected, a_r, wave amplitudes, (*B*) onshore component of the onshore directed radiation stress, S_{xx}, and (*C*) alongshore component of the onshore directed radiation stress, S_{xy}.

Reflection from a seawall causes waves to break further seaward, resulting in a steeper total water depth slope. However, the effective width of the surf zone (the distance from the seawall to the break point) is actually less than the surf zone width without a seawall. As the reflection coefficient goes to zero, the model collapses to the classical no-seawall solutions for wave setup, longshore current, and sediment transport on planar beaches. The magnitudes of the longshore current and sediment transport in front of a seawall can be either greater than or less than a similar beach without a seawall depending on the location of the seawall in the surf zone for particular choices of beach slope and wave conditions (figs. 5 and 6). A comparison with the solution to the linear long wave equation suggests that the position of the seawall serves to tune the surf zone with some positions forcing a resonant condition, causing local maxima and minima in the behavior of the integrated longshore current and sediment transport.

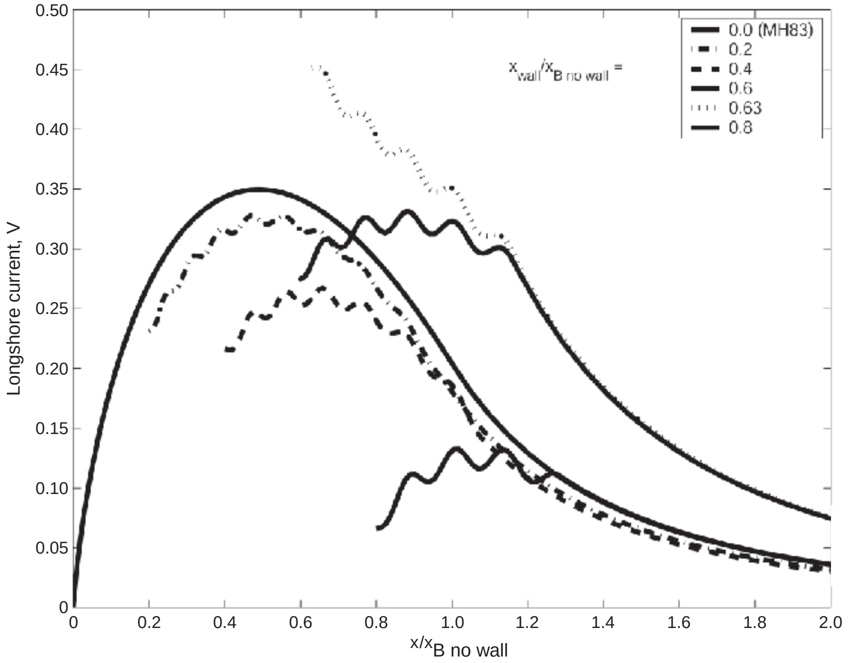

Figure 5. Longshore current profiles fronting a seawall for model case 3d (H_s = 7m, T_p = 15s, and beach slope = 1V:100H) and several positions of the wall across the surf zone. The thick solid line represents the classical longshore current solution with no seawall. The longshore current, V, has been non-dimensionalized by the longshore current at the break point and the cross-shore coordinate is non-dimensionalized by the width of the surf zone for the no-wall condition, $x_{Bnowall}$.

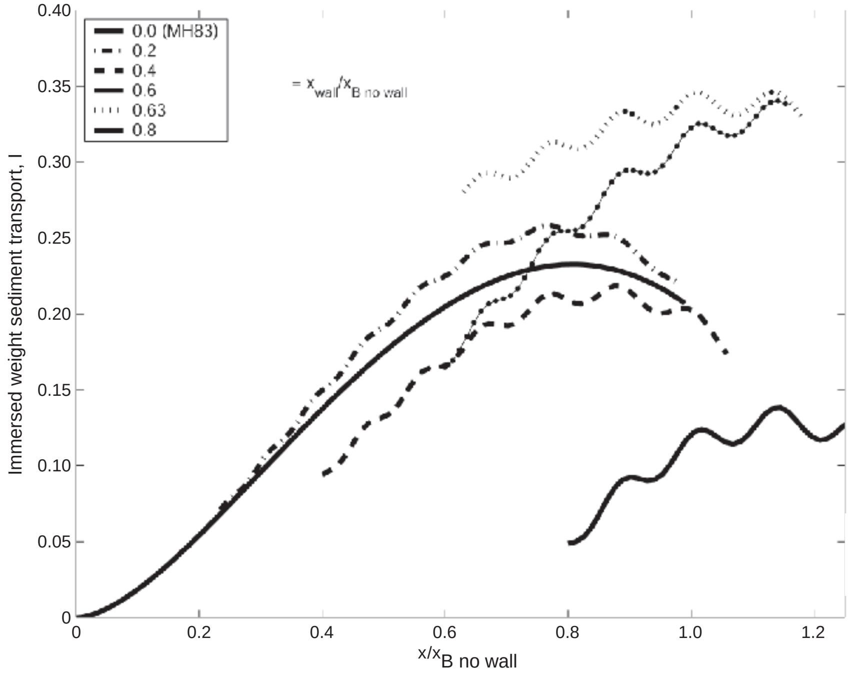

Figure 6. Sediment transport profiles fronting a seawall for model case 3d (H_s = 7m, T_p = 15s, and beach slope = 1V:100H) and several positions of the wall across the surf zone. Symbols are the same as figure 5. The non-dimensional immersed weight sediment transport, I, has been non-dimensionalized by the no seawall sediment transport evaluated at the breaker line.

Summary and Suggestions for Future Research

What remains clear is that the debate about the effect of seawalls on beaches has not been fully resolved. However, the results of the Ruggiero and McDougal (2001) study indicate potential mechanisms resulting in the contradictions in the available seawall literature. The effect of seawalls on beaches seems to be most sensitive to the position of the seawall within the surf zone, the beach slope, and the reflection coefficient, and future work should investigate these parameters in detail. Rigorous field measurements at a variety of sites with differing morphologic and hydrodynamic characteristics as well as physical and numerical modeling efforts are still necessary to provide much needed insight into the seawall problem. Therefore, testing the hypothesis that shoreline armoring activities represent one of the most dramatic sources of nearshore morphodynamic and marine habitat modification in Puget Sound is not only important locally but worldwide to beaches backed by seawalls.

To address the impacts of seawalls in the Puget Sound, we make the following suggestions regarding further study; investigations that include beach monitoring, field experiments, and numerical modeling:

5. Synthesize existing inventories of armoring trends; identify field sites for monitoring, field experiments, and modeling efforts; quantify the percentage of Puget Sound shoreline suffering from passive erosion; attempt to quantify rates (volume) of sediment source reduction as a result of shoreline armoring. (Desk Studies).

6. Develop a nearshore morphology monitoring program along walled/no-walled sections of coast. Separate short-term morphodynamic variability (active) from interannual or longer-term shoreline change trends (passive). (Field Studies).

7. Investigate the interactions between seawalls and active nearshore processes via detailed examination of the following: random high frequency fetch limited waves, complicated beach morphology and mixed sediment environment, and variable water levels changing position of seawall relative to surf zone. (Field Studies and Numerical Modeling).

References Cited

Bagnold, R.A., 1963, Beach and nearshore processes, Part I. Mechanics of marine Sedimentation, *in* Hill, M.N., ed., The Sea—Ideas and observations on progress in the study of the sea: New York, Interscience Wiley, v. 3, p. 507–528.

Bowen, A.J., 1969, The Generation of Longshore Currents on a Plane Beach: Journal of Marine Research, v. 27, p. 206–215.

Bowen, A.J., Inman, D.L., and Simmons, V.P., 1968, Wave Set-down and set-up: Journal of Geophysical Research, v. 73, p. 2569–2577.

Coyle, J., and Dethier, M.N., 2010, Review of shoreline armoring literature, *in* Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S., eds., 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010–5254, p. 245–266.

El-Bisy, M.S., 2007, Bed changes at toe of inclined seawalls: Ocean Engineering, v. 34, nos. 3–4, p. 510–517.

Fletcher, C.H., Mullane, R.A., and Richmond, B.M., 1997, Beach loss along armored shorelines on Oahu, Hawaiian Islands: Journal of Coastal Research, v. 13, no. 1, p. 209–215.

Griggs, G.B., and Tait, J.F., 1990, Beach response to the presence of a seawall—A comparison of field observations: Shore and Beach, v. 58, no. 2, p. 11–28.

Griggs, G.B., Tait, J.F., and Corona, W., 1994, The interaction of seawalls and beaches—Seven years of monitoring, Monterey Bay, California: Shore and Beach, v. 62, no. 3, p. 21–28.

Hearon, G.E, McDougal, W.G., and Komar, P.D., 1996, Long-term beach response to shore stabilization structures on the Oregon coast, *in* International Conference on Coastal Engineering, 25th, Orlando, Florida, 1996, Proceedings: Reston, Va., American Society of Civil Engineers, p. 2718–2731.

Jones, B., and Basco, D.R., 1996, Seawall effects on historically receding shorelines, *in* International Conference on Coastal Engineering, 25th, Orlando, Florida, 1996, Proceedings: Reston, Va., American Society of Civil Engineers, p. 1985–1997.

Kraus, N.C., 1987, The effects of seawalls on the beach—A literature review, *in* Coastal Sediments Conference, New Orleans, Louisiana, 1987, Proceedings: Reston, Va., American Society of Civil Engineers, p. 945–960.

Kraus, N.C., and McDougal, W.G., 1996, The effects of seawalls on the beach—Part I, An updated literature review: Journal of Coastal Research, v. 12, no. 3, p. 691–701.

Kraus, N.C., Smith, J.M., and Sollitt, C.K., 1992, SUPERTANK Laboratory Data Collection Project, *in* Coastal Engineering Conference, 23rd, Venice, Italy, 1992, Proceedings: Reston, Va., American Society of Civil Engineers, p. 2191–2204.

Lawrence, J., and Chadwick, A. J., 2005, Modelling wave reflection on sloping foreshores with sea walls: Maritime Engineering, v. 158, no. 1, p. 15–24.

Longuet-Higgens, M.S., 1970a, Longshore currents generated by obliquely incident sea waves, 1: Journal of Geophysical Research, v. 75, p. 6778–6789.

Longuet-Higgens, M.S., 1970b, Longshore currents generated by obliquely incident sea waves, 2: Journal of Geophysical Research, v. 75, p. 6790–6801.

McDougal, W.G., and Hudspeth, R.T., 1983a, Wave setup/setdown and longshore currents on non-planar beaches: Coastal Engineering, v. 7, p. 103–117.

McDougal, W.G., and Hudspeth, R.T., 1983b, Longshore sediment transport on non-planar beaches: Coastal Engineering, v. 7, p. 119–131.

McDougal, W.G., Kraus, N.C., and Ajiwibowo, H., 1996, The effects of seawalls on the beach—Part II, Numerical modelling of SUPERTANK Seawall tests: Journal of Coastal Research, v. 12, no. 3, p. 702-713.

Miles, J.R., Russel, P.E., and Huntley, D.A., 2001, Field measurements of sediment dynamics in front of a seawall: Journal of Coastal Research, v. 17, no. 1, p. 195–206.

Rakha, K.A., and Kamphuis, J.W., 1997a, Wave induced currents in the vicinity of a seawall: Coastal Engineering, v. 30, p. 23–52.

Rakha, K.A., and Kamphuis, J.W., 1997b, A morphology model for an eroding beach backed by a seawall: Coastal Engineering, v. 30, p. 53–75.

Ruggiero, P., and McDougal, W.G., 2001, An analytic model for the prediction of wave setup, longshore currents and sediment transport on beaches with seawalls: Coastal Engineering, v. 43, p. 161–182.

Weggel, J.R., 1988, Seawalls—The need for research, dimensional considerations and a suggested classification, *in* Kraus, N.C., and Pilkey, O.H., eds., The Effects of Seawalls on the Beach: Journal of Coastal Research Special Issue 4, p. 29–40.

Suggested Citation

Ruggiero, P., 2010, Impacts of shoreline armoring on sediment dynamics, *in* Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S., eds., 2010, Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009: U.S. Geological Survey Scientific Investigations Report 2010-5254, p. 179-186.