Predicting the number, orientation and spacing of dike breaches for tidal marsh restoration.

W. Gregory Hood
Skagit River System Cooperative, PO Box 368, LaConner, WA 98257, USA

ARTICLE INFO

Article history:
Received 22 March 2015
Received in revised form 13 June 2015
Accepted 4 July 2015
Available online xxx

Keywords:
Landform allometry
Tidal marsh restoration
Dike breaching
Tidal geomorphology

ABSTRACT

Tidal channels are structurally and functionally prominent features in tidal marshes, so their restoration is central to tidal marsh habitat restoration. Consequently, an important question in tidal marsh restoration is how many tidal channels can a restoration site support, and thus, how many dike breaches should be made to restore tidal inundation and tidal channels, if the dike is not to be removed entirely. Allometric analysis of reference tidal marshes in Puget Sound river deltas and the lower Columbia River Estuary showed that channel outlet count scales with marsh area, and that completed and proposed tidal marsh restoration projects had 5-fold fewer channel outlets than reference marshes. This deficiency likely impacts fish access to the restoration sites. After addressing the question of tidal channel outlet count, or dike breach count, the next design questions are how should dike breaches be oriented in tidal marsh islands and how should they be spaced. GIS and statistical analysis of reference marsh islands indicated that outlets of the two largest tidal channels draining a marsh island are typically oriented downstream, in parallel with the nearest river channel. However, the outlets of smaller tidal channels are oriented randomly. Tidal channel outlet spacing is generally independent of site size and constant within a river delta. Geometric mean spacing ranged from 122 m in the Snohomish Delta to 280 m in the North Fork Skagit Delta. These results provide important guidance to improve tidal marsh restoration design, and illustrate a useful approach to restoration design evaluation.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Tidal marshes have been historically diked, drained, and converted to agriculture or urban use, for at least a thousand years (Gedan et al., 2009). However, recent decades have seen a growing appreciation for the importance of these ecosystems in supporting commercial fisheries and wildlife, and providing shoreline protection from catastrophic storms or tsunamis (Beck et al., 2001; Gedan et al., 2011). Thus, there has been growing interest in tidal marsh habitat restoration to recover fisheries and wildlife, protect shorelines, and adapt to sea level rise accelerated by global warming (e.g., Teal and Weinstein, 2002; Weisbar et al., 2005; Wolters et al., 2005; Cui et al., 2009). Tidal marsh restoration often focuses on restoring tidal channels, because they are central to tidal marsh geomorphology and ecology. They influence hydrodynamics (Rinaldo et al., 1999), sediment transport (French and Stoddart, 1992), and the distribution and productivity of flora (Sanderson et al., 2000) and fauna (Simenstad, 1983). A common approach to tidal marsh restoration is dike breaching, where a portion of a dike is removed to return tidal inundation to a former marsh, coupled with partial excavation of an associated tidal channel to drain the marsh through the breach. Dike breaching is often preferred to complete dike removal because breaching is much less expensive. Likewise, fewer breaches are less expensive than many breaches, so the question naturally arises—how many breaches are necessary?

Previous work has shown that tidal channel planform scaling is related to hydrodynamic and ecological processes, with tidal channel size related to ebb tide flow velocity, residence time of water borne detritus, accumulation patterns of organic material in channel sediments, and the distribution of benthic detritivores, shrimp, and fish (Halpin, 1997; Hood, 2002a; Visintainer et al., 2006), and that surprising, non-linear cumulative effects are apparent in tidal channel allometry (Hood, 2007). This paper likewise uses an allometric modeling approach to show that restoration designs often plan for too few dike breaches relative to the number of tidal channel outlets that drain reference tidal marshes. Additionally, this paper examines potential patterns in outlet orientation and spacing to determine if these factors show significant patterns that should be taken into account by engineers or planners. Thus, the goal of this paper is to demonstrate a
restoration design and planning tool that can be used to predict some of the geomorphological outcomes of proposed tidal marsh restoration relevant to fish access and use of the restoration sites. By comparing restoration projects with reference marshes this paper will also show how empirical models of landform scaling can be used for restoration monitoring and evaluation. This landform scaling shows that simple, site-scale measures of channel metrics are relatively meaningless if not placed into an appropriate landscape context.

2. Methods

2.1. Study sites

Study sites were located in the lower Columbia River Estuary and Puget Sound (Washington State, USA), and included tidal marsh habitat restoration sites and their reference tidal marshes. The Columbia is the second largest river in the continental United States in terms of mean water discharge. Its drainage basin of 660,480 km² is slightly larger than France, and includes portions of

![Diagram of study site locations](image)

**Fig. 1.** Study site locations (black polygons): Puget Sound river deltas in the upper frame; the lower Columbia River Estuary from Russian Island to Whites Island, and tidal rivers tributary to Youngs Bay in the lower frame (gray = water; white = land).
the states of Washington, Oregon, Idaho, Montana, Wyoming, and Nevada, and the Canadian province of British Columbia. The Columbia River Estuary spans 240 km from the river outlet to Bonneville Dam, the lowest dam on the river, but most tidal marshes are located between river kilometers (rkm) 15 and 60, and these sites, from Russian Island to Whites Island, were the focus of this paper (Fig. 1). Additional study sites were located in Youngs Bay and its tributaries; Youngs Bay empties into the Columbia River Estuary at rkm 12, near Astoria, Oregon.

Habitat restoration in the Columbia River Estuary is driven primarily by the 2008 Biological Opinion (BiOp) issued by the National Oceanic and Atmospheric Administration Fisheries Service for the operation of federal dams on the Columbia River. The BiOp calls for habitat restoration in the Columbia River Estuary to mitigate dam impacts on Columbia River salmon, and it established an Expert Regional Technical Group (ERTG), of which the author is a member, to estimate the biological value of proposed habitat restoration projects. Restoration sites selected for this study consist of the list of dike breach or dike removal restoration projects in the lower Columbia River Estuary that were reviewed by the ERTG between 2009 and 2014.

Puget Sound is an estuarine fjord system in Western Washington, connected to the Pacific Ocean by the Strait of San Juan de Fuca and the Georgia Straight. Most Puget Sound tidal marshes are associated with river deltas. Historical tidal marsh conversion to agricultural and urban use has been extensive (Bortleson et al., 1980), but the largest extant marshes are in the Skagit (20.2 km²), Stillaguamish (9.1 km²), and Snohomish (8.1 km²) deltas (Simenstad et al., 2011). The Skagit Delta can be divided into two morphologically distinct sub-deltas formed by the two principal distributaries of the river, the North Fork and South Fork (Hood, 2007, 2015). These and the smaller Quilcene (2.6 km²), Union (1.4 km²), and Duckabush (0.4 km²) deltas, were the locations of the Puget Sound study sites.

Tidal marsh restoration in Puget Sound is driven by efforts to recover threatened Chinook (Oncorhynchus tshawytscha) and

![Graphs of tidal channel outlet count of marsh restoration sites.](image)

**Fig. 2.** Comparison of tidal channel outlet count of marsh restoration sites (white) to reference marsh islands (dark gray). Allometric regression lines are fitted to the reference marshes. Data for the Duckabush (circles) and Stillaguamish (squares) deltas are plotted on the same graph.
Chum (*Oncorhynchus keta*) salmon, which rear for many months in estuarine habitat prior to ocean residency (Magnusson and Hilborn, 2003). Information on most Puget Sound restoration projects is archived by the Washington Recreation and Conservation Office (RCO) on the PRISM (PRject Information System) web site (https://secure.rcw.wa.gov/prism/search/projectsearch.aspx). Dike breach and dike removal restoration projects were extracted from this archive. Additional dike breach/removal restoration sites included some predating the PRISM archive, but known to the author, and some that have been recently proposed by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) in a draft feasibility report and environmental impact statement (U.S. Army Corps of Engineers and Washington Department of Fish and Wildlife, 2014).

2.2. GIS and statistical analysis

Planform tidal channel and marsh metrics in this study included tidal marsh area and perimeter, and tidal channel outlet count, orientation, and spacing. These metrics were acquired by digitizing tidal marshes in georeferenced aerial photos with a GIS. The Puget Sound aerial photos had pixel resolution ranging from 15 cm to 30 cm and are described in more detail elsewhere (Hood, 2015). The Columbia River Estuary photos were 2009 true color photos acquired from the National Agriculture Imagery Program (NAIP) and had pixel resolution of 1 m. Marsh perimeters were digitized manually and did not include lengths adjacent to uplands for sites that were not islands; water or unvegetated tidal flats were easily distinguished from vegetated tidal marsh. Marsh area and perimeter were calculated by ordinary GIS routines. Tidal channel outlets along marsh perimeters were determined by visual inspection of photographs and counted for each marsh island or upland-adjacent site.

Allometric relationships were expected between marsh area and channel outlet count due to previous work (Hood, 2007, 2014). A system is allometric when the relative rate of change of one part of a system (y) is proportional to the relative rate of change of another part of the system (x), or of the whole system. Allometric models are described by power functions, \( y = ax^b \), which can be linearized through log transformation. Allometric analysis is particularly useful for comparing restoration sites with reference sites when scaling effects are expected (Hood, 2002b); the tested question is, “Do the restoration sites fit the allometric relationship that describes reference site geometry?”

Thus, all variables were log transformed for linear regression analysis to equalize variance in the residuals and fit power functions. Slopes of the log-transformed linear regression lines are equal to the exponents of the power functions, i.e., the scaling exponents. Regression lines were fitted using model 1 regression (Zar, 1984). Model 1 regression was appropriate, first because measurement error for island area was low compared to dependent channel metrics, i.e., island boundaries were easy to distinguish while small channels were comparatively more difficult to distinguish depending on vegetation cover, and second because there was a theoretical basis for a causal link between independent and dependent variables, i.e., marsh area affects the amount of tidal prism available to maintain channel form (Sokal and Rohlf, 1995).

Restoration sites were compared to reference sites through residual analysis. For each river delta, allometric regression relationships for channel outlet count were developed from the reference tidal marshes only. The deviation of the restoration sites was calculated as their residual difference from the reference marsh regression relationships. Two-way analysis of variance (ANOVA; SISTAT 13.0) using type III sums of squares determined if restoration site residuals were significantly different from those of the reference sites. The two ANOVA factors were delta location (random factor) and treatment (restoration vs. reference marsh; fixed factor).

Channel outlet orientation (azimuth) was measured relative to the centroid of each marsh island polygon for the South Fork Skagit Delta and the lower Columbia River Estuary, two locations which had a large sample size of marsh islands with 6 or more tidal channel outlets per island. The Columbia River sites were subdivided into those upstream and downstream of a large river bend where the river orientation changed from 320° to 255°. Only true islands were evaluated for channel outlet orientation. Tidal marshes adjacent to dikes or uplands were not examined, because their outlets necessarily drained in a narrow range of directions to the nearest body of water; analysis of outlet orientation would have perforce shown a non-random orientation for such sites. Lines were drawn from the centroid to each channel outlet, and the azimuth was calculated in ArcGIS for each line. Circular statistics for the mean azimuth and 95% confidence limits were calculated according to Zar (1984). The Rayleigh test was used to test for non-random distribution of channel outlet azimuths. Because the Rayleigh test was applied to each individual island, a bonferroni approximation was required which resulted in a significance threshold for the Rayleigh tests of \( p < 0.001 \). Rayleigh’s test was also applied sequentially to the set of all outlets of the largest tidal channel draining each marsh island in the South Fork Skagit Delta and the lower Columbia River Estuary (upstream and downstream subsets), then the set of all outlets of the second largest tidal channels draining each marsh island, etc., to determine whether the largest channels draining marsh islands behaved distinctly from smaller tidal channels. Channel size was determined from channel surface area. A bonferroni approximation was also applied sequentially with these tests, such that the significance threshold for the test of the second-largest channels draining each island was \( p < 0.05/2 \), for the third-largest channels it was \( p < 0.05/3 \), etc. The testing sequence terminated once a result was non-significant. Another approach to evaluating size-dependent channel outlet orientation was implemented using Chi-square goodness of fit testing. In this approach, the observed azimuth differences between the largest channels draining each marsh island and the second-, third-, nth-largest channels draining the same island were assigned to four categories: 0–45, 45–90, 90–135, and 135–180 degrees; the test’s null hypothesis was uniform.
distribution of azimuth differences among the four categories. Again, for each geographic location, goodness of fit testing was applied sequentially with decreasing channel rank, and the testing sequence was terminated once a result was non-significant.

Because channel outlet orientation relative to island centroids was generally random, channel outlet spacing was calculated by dividing the perimeter of a marsh island by the number of tidal channel outlets draining a marsh island. However, many habitat restoration projects occur on sites that are not islands, so channel outlet spacing was also calculated for marshes abutting dikes or natural uplands. In this case, the perimeter was measured only along the shoreline of these sites. Linear regression was used to determine if outlet spacing might scale allometrically with island area. When no allometry was found, two-way ANOVA compared mean outlet spacing between island marshes and upland-adjacent marshes for five sites where there was a sufficient sample size of both types of marshes, the lower Columbia River Estuary, the Young’s Bay system, the North Fork Skagit Delta, the South Fork Skagit Delta, and the Snohomish Delta.

3. Results

3.1. Channel outlet count

Two-way ANOVA indicated channel outlet count was significantly lower for restoration sites than for reference sites \(F_{1,175} = 101.15, p < 0.0001; \text{ Figs. 2 and 3}. \) There were also differences among deltas \(F_{8,175} = 3.319, p < 0.001\). After accounting for marsh size (scaling effects), tidal channel outlets on average were 3.9 times more abundant in reference marshes than restoration sites. However, restoration sites <1 ha (found only in the Skagit Delta) did not differ from reference sites in channel outlet count, because only one or two outlets are typical of reference sites this small. If these tiny sites are excluded from consideration, then tidal channel outlets were on average 5.1 times more abundant in reference marshes. Restoration site outlet counts were much lower in Snohomish Delta sites than in other locations, primarily because only one channel outlet is planned for the 162 ha Qwuloolt restoration site. The only location for which there were no
statistical differences in outlet count between reference and restoration sites was the small Duckabush Delta, which had only one small, 1 ha restoration site. Three types of restoration sites were observed: sites whose dikes were breached, sites where dikes were removed entirely, and sites where fill was removed. So the question naturally arises, which type of restoration is more likely to fully restore channel outlet count? The fill removal sites were all <1 ha and thus had channel outlet counts similar to references sites. The 17 dike breach and 16 dike removal sites were all >1 ha and their average residuals were similar, -0.687 and -0.688, respectively, with no statistical difference (t = 0.009, p = 0.99).

Two restoration projects in the lower Columbia River Estuary planned dike breaches comparable in number to those of reference marshes (Fig. 2). These projects based their design on lidar data that revealed topographic signatures of remnant historical tidal channels, with a dike breach and excavated channel planned for each channel remnant.

3.2. Channel outlet orientation

Channel outlet orientations were generally random for each marsh island. Only one of the 17 South Fork Skagit Delta marsh islands and only two of the 22 Columbia River marsh islands had channel outlets concentrated in a particular direction (downstream, p < 0.001). However, the outlets of the largest tidal channels draining each island were generally oriented downstream (Figs. 4 and 5); as a group, the largest channel outlets were not randomly distributed for the South Fork Skagit Delta (z = 11.897, n = 21, p << 0.001), nor for marsh islands upstream (z = 5.802, n = 8, p < 0.001) and downstream (z = 8.205, n = 20, p << 0.001) of a large bend in the Columbia River, where the river’s direction changed from an azimuth of 320° upstream to 255° downstream. Indeed, the mean angle of the largest channel outlets were 309° ± 28° for the upstream and 273° ± 26° for the downstream marsh islands, matching the river’s orientation. In the South Fork Skagit Delta, channel outlets for the largest channels draining a marsh island tended to be oriented in parallel to adjacent river distributaries or be directed toward the bay. The pattern was mixed for the second-largest channels draining marsh islands. In the South Fork Skagit Delta, their orientation was not distinguishable from random (z = 2.777, n = 20, p < 0.07), but in Columbia River marsh islands upstream and downstream of the river bend the second largest channel outlets had an azimuth of 305° and 221°, respectively (z = 5.875, n = 8, p < 0.001 and z = 4.986, n = 17, p < 0.01, respectively). The third largest channels were randomly oriented in all three locations (South Fork Skagit, z = 0.755, n = 18, NS; upstream Columbia River, z = 2.397, n = 8, p < 0.10; downstream Columbia River, z = 4.253, n = 15, p < 0.02).

Chi-square analysis indicated azimuth differences between the largest and second-largest channels draining marsh islands in the South Fork Skagit Delta were less than 45 degrees (χ² = 17.11; p < 0.001). The same was true for Columbia River marsh islands (χ² = 11.35; p < 0.01). Azimuth differences were random for comparisons between the largest channel and all other channel ranks.

3.3. Channel outlet spacing

Distance between channel outlets did not scale with marsh island area (Fig. 6), with p > 0.20 and R² < 0.20 for typical regressions. Two-way ANOVA on log-transformed data tested differences in outlet spacing distance for marsh islands versus upland–adjacent marsh (factor 1) among five different geographic locations (factor 2). There were no differences between island and upland–adjacent marsh (F₁,103 = 1.895; p = 0.172), but there were geographic differences (F₄,103 = 4.040; p = 0.004); pairwise comparisons (Holm–Sidak method) showed significant differences between the Snohomish Delta and both the North Fork Skagit Delta and Lower Columbia River Estuary (p < 0.05 and p < 0.005, respectively); no other pairwise comparisons were significant. There was no interaction between the two factors (F₄,103 = 1.922; p = 0.112). Geometric mean distances between channel outlets ranged from 122 m in the Snohomish Delta to 280 m in the North Fork Skagit Delta (Fig. 7).
4. Discussion

Until recently, most guidance for tidal channel engineering designs has focused on traditional hydraulic geometry of tidal channel outlet cross-sections, where tidal prism is related to channel cross-section depth, width, and area (Myrick and Leopold, 1963; Coats et al., 1995; Williams et al., 2002). This has informed engineers in designing the size of dike breaches and the depth of channel outlet excavations. However, traditional hydraulic geometry does not provide information on the number of dike breaches that should be made to restore a tidal marsh and its channel network. The allometric analysis demonstrated here and in previous papers (Hood, 2007, 2014, 2015) allows prediction of channel count, as well as total network surface area, total network length, and other aspects of planform tidal channel geometry for a given area of restoration. Prediction of total channel surface area or length, for example, allows prediction of the number of fish that might occupy the restored channel network based on typical fish densities within tidal channels and landscape connectivity (Beamer et al., 2005; Isaak et al., 2007). The analysis presented here clearly shows that completed and planned tidal marsh restoration projects are significantly deficient, by four- to five-fold on average, in dike breach count relative to the number of reference marsh channel outlets. An 80% deficit in channel outlet count diminishes fish access to dike-breach restoration sites and thereby reduces the value of the restoration project for fish, and in this case for salmon recovery in the Pacific Northwest.

A study of historical dike breach sites in Puget Sound showed a similar pattern of too few dike breaches relative to reference marsh channel outlet count (Hood, 2014). In this case, the difference was only 2.2-fold rather than 4- to 5-fold, probably because over time abandoned dikes continued to deteriorate and accumulate breaches at a rate of 1 breach per km of dike per decade. Historical dike breach sites that were many decades old (the oldest were over 80 years old) were more similar in outlet count to reference marshes than sites only a few decades old (Hood, 2014). This suggests engineering plans that underestimate dike breach count will require many decades of dike deterioration for the restoration site to become comparable to reference marshes in channel outlet count. Thus, it is important to maximize the number of initial dike...
breaches to maximize fish access to the restoration site without delay.

Tidal marsh restoration projects often involve sites adjacent to upland or reclaimed areas, such that the seaward boundaries of the project site consist of breached or removed dikes, while the landward boundaries consist of newly constructed dikes to allow agricultural, residential, or industrial land use to continue on adjacent properties. Thus, one might suspect that restoration sites could have fewer tidal channel outlets compared to marsh islands, because a portion of the restoration site’s perimeter would be adjacent to upland and not available for a channel outlet, while all of a marsh island’s perimeter would be available for a tidal channel outlet. If reference data sets were disproportionately marsh islands, while restoration sites were disproportionately upland adjacent sites, one could argue that this might be the source of the observed difference in channel outlet count. However, a previous study of tidal channel allometry in the North and South Fork Skagit River deltas has shown that dike- or upland-adjacent tidal marshes are indistinguishable from true marsh islands in channel count, as well as other planform channel metrics (Hood, 2007). Furthermore, the reference marshes in the current study consisted of six upland-adjacent marshes and three marsh islands for the Youngs Bay data set, three upland-adjacent and one island marsh for the Quilcene Delta, nine upland-adjacent and zero island marshes for the Union Delta, four upland-adjacent and one island marsh for the Duckabush marshes, and six upland-adjacent and three island marshes for the Snohomish Delta. Marsh islands were predominately only for the lower Columbia River Estuary and the Stillaguamish Delta.

Usually, tidal marsh restoration projects do not involve island sites; they involve sites bordering uplands or dikes. Nevertheless, marsh islands are useful examples of sites that have minimal constraints on tidal channel outlet location. Under these minimally constrained conditions it is clear that the largest tidal channel draining a marsh island is consistently oriented downstream. That pattern held for the second largest channel in the lower Columbia River Estuary. In the South Fork Skagit Delta orientation patterns for the second largest channels may not have been as strong as for the lower Columbia River Estuary, because delta distributary orientation was more variable than was the single-thread Columbia River channel. Thus, the Chi-square analysis of orientation differences between the 1st and 2nd largest channels draining marsh islands may be better at demonstrating the similar orientation of the two largest channels draining each marsh island in both the South Fork Skagit Delta and the lower Columbia River Estuary.

While the downstream orientation of the two largest channels draining marsh islands is noteworthy and should be emulated in restoration designs, the random orientation of smaller channels is also important, because this random orientation indicates fish access to shallow channel rearing habitat in the marsh interior is randomly dispersed around the marsh island perimeter. The random orientation of smaller tidal channels, and the fact that a geometric mean distance between channel outlets can characterize different geographic locations should not be confused with the idea that tidal channel outlets are evenly distributed among marsh island perimeters. In some cases, portions of a marsh island perimeter have relatively few channel outlets. These locations are often associated with high, natural flood-deposit levees that are covered with tidal shrub vegetation. However, these levee-zone perimeters are rarely entirely devoid of tidal channel outlets. Thus, while restoration engineers should strive to have abundant tidal channel outlets dispersed throughout the site perimeter to maximize fish access to the restoration site, an occasional dearth of outlets to accommodate anthropogenic (e.g., infrastructural) constraints on outlet location could be similar to constraints imposed by natural, flood-deposit levees in reference marsh islands—as long as those anthropogenic constraints are not too extensive.

The Puget Sound and lower Columbia River Estuary examples of tidal channel outlet deficiency in marsh restoration sites should serve as a cautionary tale to other regions where similar habitat restoration is underway or planned. It should also motivate consideration of adaptive management of already completed projects that are found to have deficiencies in dike breach number, i.e., a return to such sites to add further dike breaches.

Acknowledgements

This work was funded by the U.S. Environmental Protection Agency (grant no. PA-00j322-01). Thanks to two anonymous reviewers for helpful comments on the draft manuscript.

References


Magnusson, A., Hilborn, R., 2003. Estuarine influence on survival rates of Coho (Oncorhynchus kisutch) and Chinook salmon (Oncorhynchus tshawytscha) released from hatcheries on the U.S. Pacific Coast. Estuaries 26, 1094–1103.


