Applying tidal landform scaling to habitat restoration planning, design, and monitoring

W. Gregory Hood

Skagit River System Cooperative, PO Box 368, LaConner, WA 98257, USA

e-mail: ghood@skagitcoop.org

Abstract

Tidal channels are structurally and functionally prominent features in tidal marshes, so their restoration is central to marsh restoration. Prominent design questions in tidal marsh restoration include: 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? How much total channel surface area will be supported by a restored marsh, and thus, how many fish, shrimp, or other organisms can be supported by restored channel habitat? These basic design questions can be addressed by landscape allometry, which describes the proportional relative rates of change in a system between two entities of particular interest—in the case of marsh restoration, between the amount of marsh area to be restored and a wide variety of measures of tidal channel network geometry. This paper briefly reviews the development of landscape allometry, insights that it provides into landforms and related ecological patterns, and its utility and application to marsh restoration planning, design and monitoring. Its practical application is illustrated in a conceptual restoration design that is the basis for a current restoration project.

KEYWORDS: marshes; habitat restoration; tidal channels; landscape allometry

REGIONAL INDEX TERMS: USA, Washington, Puget Sound

1. Introduction

For at least the last millennium, human land use practices have been responsible for the extensive destruction of coastal wetlands. In many areas of the world, losses have exceeded 50% due to diking and draining of coastal wetlands for conversion to agricultural or urban use (Davy et al., 2009; Gedan et al. 2009). Additional impacts have resulted from construction of large dams that trap river sediments, diversion of river flows to agricultural or urban use, and extraction of oil, gas, and groundwater leading to subsidence in river deltas (Syvitski 2008). Dredging estuarine waterways for navigation has led to systemic changes in tidal range, tidal excursion, salinity intrusion, storm surge propagation, and sediment transport with consequent impacts to coastal wetland productivity and sustainability (DiLorenzo et al. 1993; Cox et al. 2003; Van Maren et al. 2015). However, within the last few decades we have discovered that tidal marshes provide a wide variety of important ecosystem services. For example, tidal marshes are important nurseries for commercial fisheries and refuges for wildlife, provide shoreline protection against storms and tsunamis, filter and transform potentially harmful nutrients, and provide valued recreational opportunities (Costanza et al. 1997; Beck et al. 2001; Barbier et al. 2011; Gedan et al. 2011; Smyth et al. 2012). This comparatively recent appreciation for tidal marsh ecosystem services has led to interest in tidal marsh restoration to recover fisheries and wildlife, protect shorelines, ameliorate nutrient pollution, sequester carbon, and adapt to sea level rise accelerated by global warming (e.g., Hilderbrands et al. 2005; Wolters et al. 2005; Elliott et al. 2007; Gedan et al. 2009; Cui et al. 2009; Roman and Burdick 2012).

Predicting restoration outcomes is essential in planning restoration projects to achieve restoration goals, anticipate indirect effects on the system, avoid or mitigate impacts to adjacent land owners, and maximize benefits while minimizing costs. Prediction failures can have significant ecological, financial, and political costs, making implementation of future restoration projects more difficult. Conversely, prediction successes can improve project efficiencies and generate increasing confidence in future restoration proposals by the public, funding agencies, and political authorities.

A variety of approaches and models are used for tidal marsh restoration planning and prediction, including: [1] simply attempting to imitate a nearby reference site, which occurs when there is relatively little understanding of a system; [2] conceptual models, which are used when there is qualitative, but little quantitative understanding of a system (Chow-Fraser 1998; Ogden et al. 2005; Fischenich 2008); [3] empirical statistical models, e.g., application of hydraulic geometry to tidal channel design, where landforms can be well quantified, but the responsible physical mechanisms may not be (Williams et al. 2002); and [4] numerical modeling, when hydrodynamic and morphodynamic processes are well quantified (e.g., D'Alpaos et al. 2007; Yang et al. 2010a, b). All of these approaches try to mimic a natural template, which is implicitly assumed to be an expression of a dynamic equilibrium state, subject to local geophysical controls on landform and ecosystems, and thus inherently stable or sustainable. Additionally, it is assumed that native fish and wildlife are evolutionarily adapted to the natural template, but less so to alternate system states. Important exceptions, where these assumptions are not valid, are systems in highly modified anthropogenic landscapes that are unlikely to ever be fully restored to a natural state, e.g., very urbanized waterways

(Simenstad et al. 2005; Cox et al. 2006). Here the choice may be between attempting very limited restoration of natural conditions or creating a tolerable alternate state, depending on anthropogenic constraints.

Typically, restoration planners use all available prediction tools, because some are useful at different scales, answer different questions, or are dependent on different constraints on available information. In this paper, I will focus on a descriptive empirical model that I term landscape allometry, which has roots in the literature of hydraulic geometry and landform scaling. This paper will summarize recent developments in landscape allometry, and describe its utility and application to tidal marsh restoration.

A critical issue in tidal marsh restoration, and thus the focus of the model to be discussed, is the restoration of tidal channels. Tidal channel geometry and channel and marsh hydrodynamics interact in complicated feedbacks via sediment erosion, deposition, and transport (e.g., French and Stoddart 1992; Friedrichs 1995; Lawrence et al. 2004; Fagherazzi et al. 2008), while channel hydrodynamics also play a central role in the movement of nutrients, detritus, aquatic organisms, and pollutants between the tidal marsh and adjacent waters such as rivers, bays, and the ocean (e.g., Simenstad 1983; Odum 1984; Rozas et al. 1988; Temmerman et al. 2005). These interactions, in turn, affect the distribution and production of flora (Sanderson et al. 2000) and fauna (Levy and Northcote 1982; Halpin 1997; Williams and Zedler 1999; Hood 2002a). Thus, understanding and predicting tidal channel geometry is key to understanding and restoring geophysical and ecological processes in tidal marshes and associated tidal flats (Spencer and Harvey 2012).

2. Landscape allometry

A wide variety of landforms are known to scale, that is to be similar in form regardless of the scale at which they are observed (e.g., Rodriguez-Iturbe and Rinaldo 1997; Dodds and Rothman 2000). Strict self-similarity is relatively uncommon in landforms; more common is self-affinity, where form scales differently in different directions, i.e., the form is squashed or stretched in a regular fashion in one or more directions as it changes size or as the scale of observation changes. Such self-affinity is also known as allometry (Mandelbrot 1983; Ouchi and Matsushita 1992). The relationship between form and measurement scale is typically the focus of fractal geometry. The allometric tradition, best exemplified in anatomy, physiology, and physiological ecology, focuses on proportional relative rates of change in a system between two measured quantities of particular interest. In organismal biology the relationship is often between body mass and another variable, such as metabolic rate, growth rate, swimming, running, or flying speed, and home range size (e.g., Schmidt-Nielsen 1984). However, allometry has also been applied to the study of landforms, such as river basins, channels, deltas, dolines, glacial cirques, and drumlins (Woldenberg, 1966; Bull, 1975; Kemmerly 1976; Church and Mark, 1980; Evans 2010; Wolinsky et al. 2010).

There is some disagreement over whether tidal channel systems scale. Some investigators have found evidence, primarily in the marshes of the Venice Lagoon, that they do not (e.g., Rinaldo et al. 1999a; Feola et al. 2005), and suggest spatial heterogeneity in resistance to erosion in different sedimentary layers and regions of the marsh system may be responsible for the lack of scaling (Fagherazzi and Furbish 2001), or that strong spatial gradients of landscape-forming flows (e.g., fluvial to tidal) and interactions of competing dynamic processes may confound scale-invariant patterns (Rinaldo et al. 2004). Nevertheless, some aspects of the Venetian system (the relationships between channel width and peak discharge, tidal watershed area, and flow) do show well-defined scaling behavior (Rinaldo et al. 1999b). In many other tidal channel systems, investigators claim unambiguous evidence of scaling (e.g., Cleveringa and Oost, 1999; Angeles et al., 2004; Novakowski et al., 2004; Jiménez et al., 2014). In the tidal marshes of the Skagit River delta (Puget Sound, Washington, USA at approximately 48° 18′ N, 122° 22′ W), scaling relationships have been found for a wide variety of channel network metrics (e.g., total channel length, total channel surface area, channel count) and marsh island surface area. These scaling relationships were accurately replicated by a recursive simulation model of tidal channel formation through the predominantly depositional sedimentary processes that have been observed in this system (Hood 2006, 2007, 2016). This is noteworthy because recursive processes underlie fractal behavior.

3. Methods

Allometric scaling relationships between two variables of interest are described by a power function, $y = ax^b$, where a and b are fitted constants that are characteristic of the system. Log-transformation of the power function yields a linear equation, $\log y = \log a + b \log x$, where b is the slope of the line and $\log m$ is the y-intercept. Data are typically plotted on log-transformed axes to produce straight regression lines, but linear regression analysis must be done on log-transformed data. Log-transformation has the additional benefit of normalizing the data and equalizing variance, basic pre-requisites for linear regression.

Model II regression is often advocated when geomorphic variables are analyzed, because both the *x* and *y* variables are subject to natural variation and measurement error (Mark and Church 1977). Model I regression assumes the *x* variable is subject to neither, but is under control of the investigator, e.g., in a manipulative experiment. Estimates of the slope and intercept of the fitted linear regression are biased when Model I regression is applied under circumstances that call for Model II regression. Nevertheless, Model I regression is required when the aim is prediction (Sokal and Rohlf 1995), as is the case for the current discussion. Additionally, Model I regression can be used if measurement error is low for the x-variable compared to the y-variable, or if there is a theoretical basis for a causal link between both variables (Sokal and Rohlf 1995). The former condition is the case, for example, when the *x*-variable is marsh island surface area and the *y*-variable is total tidal channel length or total channel surface area. Marsh Island perimeters can be relatively easily identified in aerial photos and digitized in GIS, but tidal channels can be missed or their banks hard to locate if photo resolution is poor or if vegetation canopies (even those of sedges or grasses) overhang and obscure smaller channels, factors which disproportionately affect small channels. The latter condition (causality) is pertinent in this example, because marsh area affects the amount of tidal prism available to maintain channel form. Finally, Model I and Model II regression produce the same slope and intercept estimates when R^2 values are high, i.e., ≥ 0.90; Model I estimate bias increases as R^2 decreases.

If the forms being analyzed do not change shape with changing size, then they are isometric and the regression slopes (= power function exponents) will be equal to predictions from dimensional analysis, which serve as a kind of null hypothesis. For example, if a set of rectangles does not change shape with changing size, then a linear dimension of the rectangles (e.g., width) will scale with area as, $W = \mathrm{k}A^{0.5}$, where k is a fitted constant characteristic of the shape (e.g., circle vs. square). If the forms do change shape with size, then one dimension changes at a different rate from the other, so the regression slope will differ from the dimensional null and the forms are allometric.

Regression intercepts are often ignored in fractal analysis, because they are considered to convey no meaningful information, but in allometric analysis the intercepts are meaningful. For example, home range size versus body mass scales similarly for carnivores and herbivores; both trophic groups have the same linear regression slope. However, the regression intercepts differ between both groups. Home range size is about ten times larger for carnivores than herbivores at any given body mass, reflecting energetic inefficiencies in transferring energy from one trophic level to the other (Tucker et al. 2014). Similarly, for tidal channel allometry relative to marsh area, similar scaling exponents have been found among different river delta systems in Puget Sound, but meaningful intercept differences reflect the influence of marsh erosion (Hood 2007), tide range, wind fetch, or sediment supply on channel size and count independently of marsh island area (Hood 2015). It is likely that other factors, such as sediment grain size, vegetation canopy height, density, and flexibility, would also affect allometric intercepts if not the scaling exponent.

4. Tidal channel allometry

Tidal channel allometry has developed by extension of hydraulic geometry, where tidal prism has replaced river discharge as the predictor of channel cross-sectional area, width, and depth (Myrick and Leopold 1963, Williams et al. 2002). The relationship between tidal prism and channel cross-section geometry can be integrated over the whole channel network, so that tidal prism can predict total channel length and surface area. Further, just as drainage basin area can substitute for river discharge to predict cross-sectional geometry and river length (Hack 1957; Rodriguez-Iturbe and Rinaldo 1997), tidal drainage basin area can substitute for tidal prism to predict tidal channel geometry (Williams et al. 2002; Novakowski et al. 2003). Assuming tidal landscapes are fractal, like many other landscapes, allows the conceptual extension from tightly coupled individual tidal basin-tidal channel scaling to more diffusely coupled marsh island-island channel network scaling. In this extension, marsh islands are the geomorphic unit rather than individual tidal channel drainage basins. The response variable is the network of tidal channels draining a marsh island, rather than an individual tidal channel. The coupling is more diffuse because the marsh island tidal prism is not entirely directed towards the channel network; a portion, that is typically poorly quantified, is flow that drains directly from the island margins into adjacent waters, while the remaining flow is apportioned to various channels in the drainage network with no obvious constraint on how it is apportioned.

A focus on the allometry of marsh islands and their channel networks provides some key insights into tidal landforms, relevant to marsh restoration, that a more traditional, single channel, hydraulic geometry approach does not. For example, in Puget Sound river deltas, total channel length scales with marsh island area with an exponent of 1.24, while total channel surface area scales with an exponent of 1.52 (Hood 2015). Scaling exponents >1 mean that the response variable increases faster than does the independent variable, i.e., on average, a 100-

ha tidal marsh has more total channel length and surface area than do two 50-ha marshes, and each 50-ha marsh has more than two 25-ha marshes, etc. If a restoration goal is to maximize tidal channel habitat for fish and wildlife, this non-linear cumulative effect of marsh area on total channel surface area and length suggests one should prioritize restoration of large contiguous marshes over several isolated smaller marshes. Of course, the landscape scale organization of several small tidal marshes, for example as a stepping stone migratory corridor, may be an additional consideration that offsets the value of a single large site.

Another example of the utility of tidal channel allometry is that it can predict how many tidal channels a given area of restored marsh should have, while traditional single-channel hydraulic geometry cannot. For example, in the influential design guidance document by Coats et al. (1995), the question was posed of how to determine the appropriate planform tidal channel geometry for a hypothetical 16-ha restoration site. Using traditional hydraulic geometry, two of several possible solutions were presented; one consisted of a single large 4th-order tidal channel, the other consisted of four 3rd-order channels. Each of the several solutions was implied to be equally likely. However, an allometric approach to design provides an unambiguous prediction of the number of tidal channels such a site should most likely have (Hood, 2007, 2015a), as well as their size distribution (Hood 2016).

The number of tidal channels that should drain a restoration site appears to be often severely underestimated by project planners and engineers. A review of tidal marsh restoration projects in Puget Sound and the Columbia River Estuary, using allometric analysis, found that, on average, one-fifth the number of tidal channel outlets drained restoration sites as did reference tidal marshes (Hood 2015b). While not yet empirically tested, such a severe deficiency in tidal channel outlets presumably impacts juvenile salmon accessibility to the restored tidal marshes, which is particularly unfortunate because recovery of threatened salmon is the primary motivating impulse for tidal marsh restoration in this region. Other impacts to hydrodynamic fluxes of water and water-borne materials might also result from this geomorphic deficiency.

This example additionally illustrates the utility of allometric landform analysis for monitoring or evaluating tidal marsh restoration projects. One problem sometimes encountered in restoration monitoring is finding enough appropriate reference sites to have a sufficient sample size to do an analysis of variance (ANOVA) or analysis of similarity (ANOSIM), common ways to test for statistically significant differences between treatment and reference sites. Reference sites may sometimes be deemed too different from the restoration site to included in such analyses because they are physically very different, e.g., the tidal channels are very different in size and thus so are their hydrodynamics and dependent biological structures and processes, or the sites have very different salinities. Allometric analysis effectively treats differences in channel size or marsh area as covariates in an analysis of covariance (ANCOVA), which loosens the constraints on qualifying as a useful reference site (Hood 2002b).

Finally, unlike hydraulic geometry, allometric analysis can be used as a diagnostic tool to reveal sometimes unexpected anthropogenic impacts. For example, tidal channels in the oligohaline portion of the Chehalis River Estuary (in Washington State at approximately 46° 57’ N, 123° 42’ W) have a border of intertidal sedge (*Carex lyngbyei*) interposed between the channel and a supratidal river floodplain wetland characterized by freshwater wetland shrubs, Sitka spruce trees (*Picea sitchensis*), and a freshwater sedge (*C. obnupta*). The width of the intertidal sedge border scales allometrically with channel width—border width increases with channel width—except for the largest tidal channels where sedge border widths deviate suddenly from the allometric pattern and are generally as small as the intertidal sedge borders in the smallest channels (Hood 2002b). Historical photos from the 1940s to the 1980s reveal that the largest tidal channels were used intensively for log storage and transport as part of timber harvest activities in nearby forested uplands. Pilings, which helped anchor log rafts, are still present in the largest tidal channels, but not in the others. Log handling and storage is known to destroy intertidal vegetation by scouring the vegetation directly and by smothering the vegetation with sloughed bark and wood debris (Sedell and Duval 1985). Thus, the largest channels likely had much wider intertidal sedge borders historically, but today only narrow, eroded, intertidal sedge remnants can be found. Without allometric analysis this historical anthropogenic impact to intertidal sedge habitat would have remained cryptic.

5. Application to restoration

An allometric approach to tidal channel network prediction has practical value for tidal marsh restoration planning and design, precisely because it focuses on relationships between two measured quantities of interest, e.g., the amount (surface area) of marsh to be restored and the amount (total length, total surface area or channel count) of tidal channel to be restored. A case study follows that illustrates practical application of tidal channel allometry to restoration conceptual design.

5.1. The zis a ba restoration project

A former farm site of 33.6 ha in the Stillaguamish Delta (Puget Sound, Washington, USA, 48° 14’ 10” N, 122° 22’ 18” W) has been proposed for restoration to tidal marsh habitat with the primary goal of benefitting juvenile salmon. Dike removal will restore tidal inundation to the site, which was historically a tidal marsh. Tidal channels are expected to develop on the site, but there is concern they may cross over and expose two buried pipelines that bisect the site. The pipelines lie immediately next to one another, approximately 1.3-2.0 m below grade. Rather than allowing passive development through tidal erosion, channels will be excavated to control their location and thereby protect the buried pipelines. The pipeline will also be protected by armoring its length with a mound of soil. This will produce a drainage divide that bisects the site and discourages channel encroachment of the pipeline. Channel excavation will also accelerate channel development so that fish use can occur as quickly as possible, maximizing benefit to the fish. Otherwise a lag of several decades may occur before the channel network develops (Shi et al. 1995, D’Alpaos et al. 2007, Hughes et al. 2009), during which time fish use is impaired.

Several questions needed to be addressed regarding tidal channel design: [1] How many tidal channels should drain the project site? [2] Where should the tidal channels be located on the site? [3] How large (long) should the tidal channels be? [4] How deep might the tidal channels become? The first three questions were answered by using allometric analysis of tidal channels of the nearby South Fork Skagit Delta and Stillaguamish Delta marshes as reference standards for the desired planform geometry of the restoration site channels, and by using available lidar data to situate the proposed tidal channel network. The last question was addressed by using traditional hydraulic geometry, with tidal basin area substituting for tidal prism as the predictor of channel depth. After channel planforms were established, basin divides were estimated with a GIS as the equidistant points between channel polygons. Only the prediction of planform geometry through allometric analysis is discussed further.

Because the restoration site is bisected by buried pipelines, whose protection will create a large drainage divide, the site was treated as two parcels. For the purpose of allometric analysis of tidal channel geometry (Hood 2007), the area of each restoration site parcel included the existing marsh, adjacent to the dikes, because the intention is to remove almost all of the dikes, so that there is free tidal exchange across the existing fringing marsh and the restored marsh. Thus, the western parcel amounts to approximately 23.5 ha and the eastern parcel to 18.4 ha.

5.2. Where should channels be located?

The first step in the design process was to look for opportunities for tidal channel placement. This was done by consulting the lidar data and selecting low linear topography that would likely develop into channels following tidal restoration, either through passive erosion or active excavation. Active excavation would accelerate channel development and exert greater control over its location, which was desirable to avoid the buried pipelines. Potential channel locations were drawn by eye in a GIS to form linear features that connected low topography (Fig. 1). Channel outlet locations were selected that might involve minimal excavation to connect low topographic areas to the marsh margin. The only additional constraint on channel location was that they had to avoid the buried pipelines. Following this initial depiction of tidal

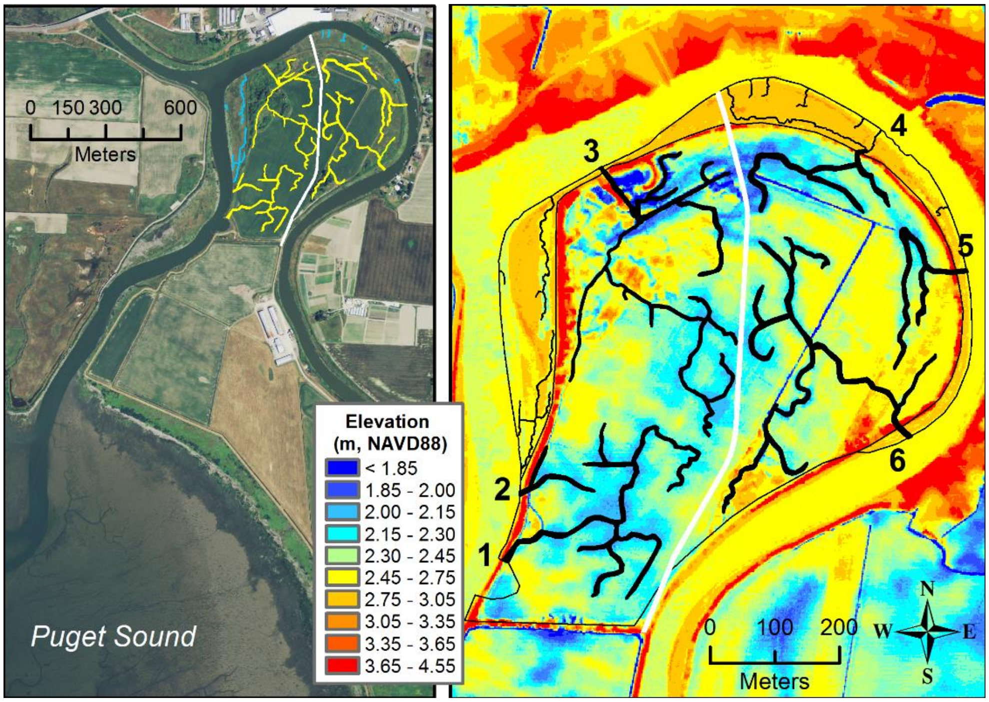

Fig. 1. Conceptual tidal channel design for the zis a ba restoration site. The left frame shows the site context, adjacent to the Stillaguamish tidal slough that flows from east to west, then bifurcates west of the site to flow north into Skagit Bay and south into Port Susan Bay, both embayments of Puget Sound. Yellow channels in the left frame are proposed for excavation; blue channels are extant in the adjacent local reference marsh. In the right frame, depicting lidar-based topography, narrow black channels are extant channels in the local reference marsh; thick black channels (numbered) are proposed for excavation. The buried pipelines are depicted in white in both frames.

channel location and extent, allometric analysis was used to determine if the initial channel planform geometry was comparable to reference marsh conditions. In particular, was the initial design comparable in the number of channel outlets, total channel length, and length distribution of the individual channels.

5.3. How many tidal channels?

Two local reference marsh areas were selected to represent geomorphological conditions in the immediate vicinity of the restoration site; they were the existing fringing marsh immediately adjacent to the west and north of the dikes enclosing the site. These were then compared to allometric patterns from tidal marshes of the nearby North Fork and South Fork Skagit deltas north of the restoration site, as well as the active Stillaguamish Delta just to the south. The restoration site is located in a relatively sheltered area, similar to the South Fork Skagit Delta. In contrast, the North Fork Skagit and active Stillaguamish deltas are exposed to large fetch. Because fetch affects channel geometry (Hood 2015a), the South Fork Delta was expected to be the best reference system for the restoration site, and indeed the two local reference marshes adjacent to the restoration site were most similar in channel count, total channel length, and the length of the largest channel draining a marsh island to the marsh islands in the South Fork Skagit Delta (Fig. 2). Thus, the South Fork allometric relationship was used to generate an estimate of the appropriate channel outlet count for the restoration site. The restoration site as a whole, along with its existing fringing marsh, was predicted to have 17 tidal channels draining the area, with a lower 80% confidence limit of the prediction (CLP) of 9 channel outlets and an upper 80% CLP of 39 channel outlets. Currently, 11 tidal channel outlets

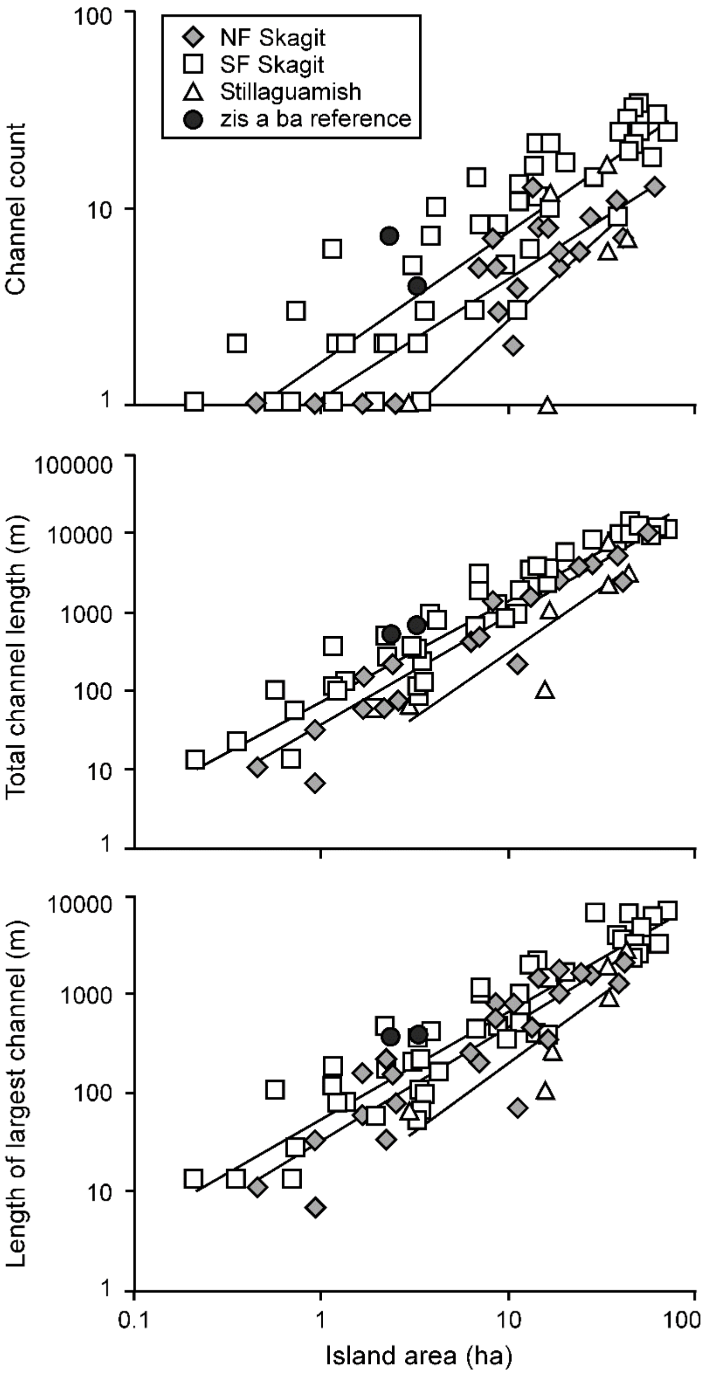

Fig. 2. Comparison of tidal channel geometry between two reference marsh sites adjacent to the zis a ba restoration project site and marshes in the North Fork Skagit, South Fork Skagit, and Stillaguamish deltas.

empty from the marsh bordering the restoration site. The initial conceptual design presented above envisioned excavation of 6 additional tidal channels, 5 of which drain through new tidal channel outlets, producing a total of 16 tidal channel outlets, close to the allometric prediction.

5.4. How large should the channels be?

The lengths of the three excavated tidal channels (generally larger than those extant in the adjacent fringing marsh) in each of the west and east parcels in the initial conceptual design, and the largest channel in the western and northern adjacent fringing marsh were compared to the Skagit South Fork Delta reference marshes using allometric analysis. Tidal channel lengths of the initial conceptual design were generally consistent with those of the reference marshes (Fig. 3). The tidal channel that most deviated from the reference marsh allometry was an extant channel in the adjacent fringing marsh that would be the fourth largest channel in the east parcel. The tidal channel in the fringing marsh adjacent to the west parcel would be the third largest for that parcel, and was consistent with the reference marsh allometry.

6. Summary

In the above case-study, allometry is shown to be a useful tool for testing whether a preliminary conceptual design for tidal channel restoration conforms to a reference marsh planform geometry. In this instance, the use of lidar for design guidance led to an appropriate channel planform conceptual design that formed the basis for later engineering plans. Other

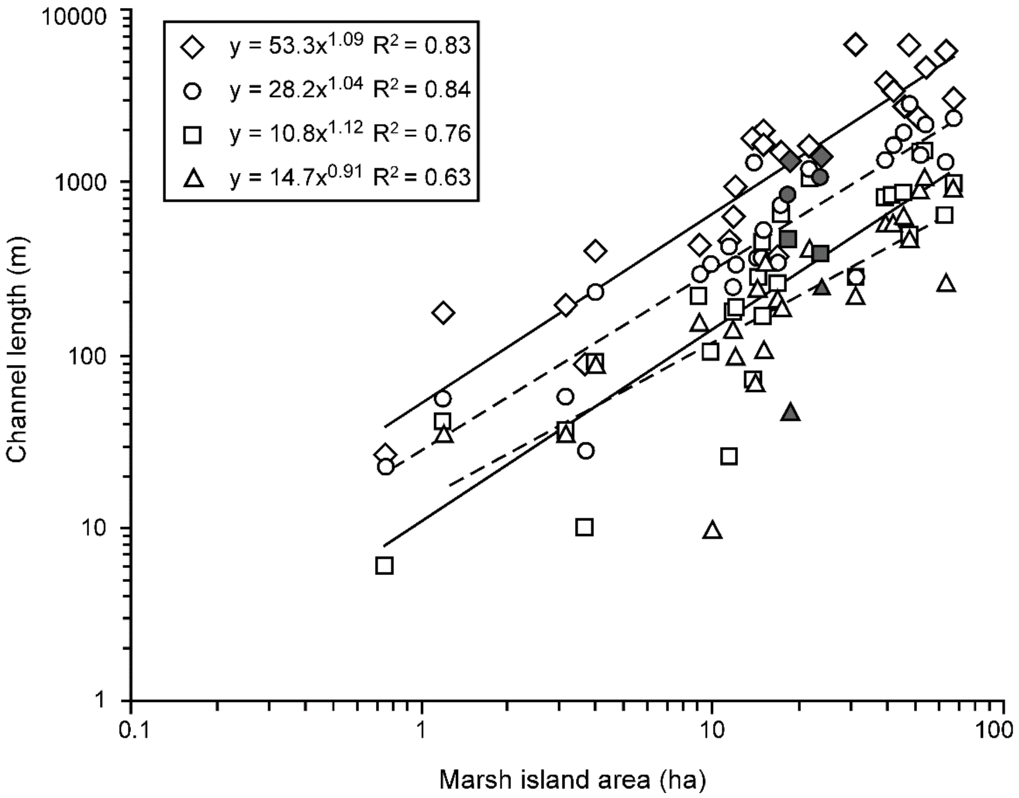

Fig. 3. Scaling of the largest (diamonds), second largest (circles), third largest (squares), and fourth largest (triangles) tidal channels draining South Fork Skagit Delta marsh islands (open symbols), compared to the largest through fourth largest proposed tidal channels draining the west and east parcels of the zis a ba restoration site (filled symbols).

systems with a longer history of anthropogenic disturbance may be less likely to provide similarly useful topographic guidance. In such cases, there is likely less constraint on tidal channel location and their location might be determined by other project-specific criteria or local circumstances. Nevertheless, reference marsh allometry can provide channel network-scale guidance on the number and size of channels to be expected within the system's geophysical constraints.

Allometric analysis of tidal channels and marsh islands allows prediction of a wide variety of characteristics of a population of tidal channels draining a marsh island, e.g., total channel length, total channel area, total channel magnitude (number of first order channels), channel count, as well as the geometry of the largest, second-largest, third-largest, etc., tidal channels draining a marsh island (Hood 2007, 2015b). Biological responses to landforms have also been shown to fit allometric patterns, e.g., the width of sedge borders along tidal channels that dissect river floodplain swamps, and the distribution and abundance of detritus, sediment carbon content, benthic invertebrate detritivores, and fish in tidal channels of varying size (Hood 2002a, 2002b,). Exploration of these scaling patterns is still in its infancy, as is application of landscape allometry to habitat restoration. There is a great need to further document examples of landform and eco-landform scaling, to better develop integrated modeling methods that incorporate these scaling results, and to develop protocols for their practical application in ecosystem management. Better recognition and appreciation of landscape allometry (eco-landform scaling) would lead to better restoration planning, design, and monitoring.

Acknowledgements

This work funded by the U.S. Environmental Protection Agency (grant no. PA-00J322-01), as well as a contract with the Stillaguamish Tribe to develop a conceptual restoration design for the zis a ba restoration site.

References

Angeles, G.R., Perillo, G.M., Piccolo, M.C., Pierini, J.O., 2004. Fractal analysis of tidal channels in the Bahía Blanca Estuary (Argentina). Geomorphology 57, 263–274.

Barbier, E.B., Hacker, S.D., Kennedy, C., et al., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169-193.

Beck, M.W., Heck Jr, K.L., Able, K.W., et al., 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. Bioscience 51, 633– 641.

Bull, W.B., 1975. Allometric change of landforms. Geol. Soc. Am. Bull. 86, 1489–1498.

Church, M., Mark, D.M., 1980. On size and scale in geomorphology. Progr. Phys. Geogr. 4, 342-390.

Chow-Fraser, P., 1998. A conceptual ecological model to aid restoration of Cootes Paradise Marsh, a degraded coastal wetland of Lake Ontario, Canada. Wetlands Ecol. Manage. 6, 43-57.

Cleveringa, J., Oost, A.P., 1999. The fractal geometry of tidal-channel systems in theDutch Wadden Sea. Geol. Mijnbouw 78, 21–30.

Coats, R.N., Williams, P.B., Cuffe, C.K., et al.,1995. Design Guidelines for Tidal Channels in Coastal Wetlands, Rep. 934, U. S.Army Corps of Engineers. Waterways Experiment Station Vicksburg, MS.

Costanza R, D’Arge R, DeGroot R, et al., 1997. The value of the world’s ecosystem services and natural capital. Nature 387, 253–80.

Cox, R., Wadsworth, R.A. and Thomson, A.G., 2003. Long-term changes in salt marsh extent affected by channel deepening in a modified estuary. Continental Shelf Res. 23, 1833-1846.

Cox, T., Maris, T., De Vleeschauwer, P., et al., 2006. Flood control areas as an opportunity to restore estuarine habitat. Ecol. Eng. 28, 55-63.

Cui, B., Yang, Q., Yang, Z., et al., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. Ecol. Eng. 35, 1090–1103.

D'Alpaos, A., Lanzoni, S., Marani, M., et al., 2007. Spontaneous tidal network formation within a constructed salt marsh: Observations and morphodynamic modelling. Geomorphology 91, 186-197.

Davy, A.J., Bakker, J.P., Figueroa, M.E., 2009. Human modification of European salt marshes. In: Silliman, B.R., Grosholz, E., Bertness, M.D. (Eds.), Human Impacts on Salt Marshes: A Global Perspective. University of California Press, Berkeley and Los Angeles, pp. 311–336.

DiLorenzo, J.L., Huang, P., Thatcher, M.L., et al., 1993. September. Dredging impacts on Delaware Estuary tides. In: Bedford, K., Blumberg, A., Spaulding, M.L. (Eds.), Estuarine and Coastal Modeling III: Proceedings of the 3rd International Conference. Am. Soc. Civil Eng., Reston, VA., pp. 86-104.

Dodds, P.S., Rothman, D.H., 2000. Scaling, universality, and geomorphology. Ann. Rev. Earth Planet. Sci. 28, 571–610.

Elliott, M., Burdon, D., Hemmingway, K.L., et al., 2007. Estuarine, coastal and marine ecosystem restoration: confusing management and science: A revision of concepts. Estuar. Coast. Shelf Sci. 74, 349-366.

Evans, I.S., 2010. Allometry, scaling, and scale specificity of cirques, landslides and other landforms. Trans. Japan. Geomorph. Union 31, 133-153.

Fagherazzi, S., Hannion, M., D'Odorico, P., 2008. Geomorphic structure of tidal hydrodynamics in salt marsh creeks. Water Resour. Res. 44**,** W02419, doi:10.1029/2007WR006289.

Fagherazzi, S., Furbish, D.J., 2001. On the shape and widening of salt marsh creeks. J. Geophys. Res. 106 (Cl), 991–1003.

Feola, A., Belluco, D., D'Alpaos, A., et al., 2005. A geomorphic study of lagoonal landforms. Water Resour. Res. 41, W06019, doi: 10.1029/2004WR003811.

Fischenich, C., 2008. The application of conceptual models to ecosystem restoration. Publication No. ERDC/EBA-TN-08-1. Engineer Research and Development Center, Vicksburg, MS Coastal and Hydraulics Lab.

Friedrichs, C.T., 1995. Stability shear stress and equilibrium cross-sectional geometry of sheltered tidal channels. J. Coast. Res. 11, 1062-1074.

French, J.R., Stoddart, D.R., 1992. Hydrodynamics of salt marsh creek systems: implications for marsh morphological development and material exchange. Earth Surf. Process. Landforms 17, 235–252.

Gedan, K.B., Kirwan, M.L., Wolanski, E., et al., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Climatic Change 106, 7-29.

Gedan, K.B., Silliman, B.R., Bertness, M.D., 2009. Centuries of human-driven change in salt marsh ecosystems. Ann. Rev. Mar. Sci. 1, 117–141.

Hack, J., 1957. Studies of longitudinal stream profiles in Virginia and Maryland, U.S. Geol. Surv. Prof. Pap., 294-B.

Halpin, P.M., 1997. Habitat use patterns of the mummichog, Fundulus heteroclitus, in New England. I. Intramarsh variation, Estuaries, 20, 618– 625.

Hilderbrand, R.H., Watts, A.C., Randle A.M., 2005. The myths of restoration ecology. Ecology and Society 10(1), 19.

Hood, W.G., 2016. Parallel scaling of tidal channel length and surface area with marsh area for 1st through Kth-ranked channels and their tributaries: Application for tidal marsh restoration. Ecol. Eng. 95, 54-63.

Hood, W.G. 2015a. Geographic variation in Puget Sound tidal channel planform geometry. Geomorphology 230, 98-108.

Hood, W.G., 2015b. Predicting the number, orientation, and spacing of dike breaches for tidal marsh restoration. Ecol. Eng. 83, 319-327.

Hood, W.G., 2007. Scaling tidal channel geometry with marsh island area: a tool for habitat restoration, linked to channel formation process. Water Resour. Res. 43, W03409, doi:10.1029/2006WR005083.

Hood, W.G., 2006. A conceptual model of depositional, rather than erosional, tidal channel development in the rapidly prograding Skagit River Delta (Washington, USA). Earth Surf. Process. Landforms 31, 1824-1838 doi: 10.1002/esp.1381.

Hood, W.G., 2002a. Landscape allometry: From tidal channel hydraulic geometry to benthic ecology, Can. J. Fish. Aquat. Sci., 59, 1418–1427.

Hood, W.G., 2002b. Application of landscape allometry to restoration ecology. Restoration Ecol. 10, 213-222.

Hughes Z.J., FitzGerald, D.M., Wilson, C.A., et al., 2009. Rapid headward erosion of marsh creeks in response to relative sea level rise. Geophys. Res. Lett. 36, L03602, doi:10.1029/2008GL036000.

Jiménez, M., Castanedo, S., Zhou, Z., et al., 2014. Scaling properties of tidal networks. Water Resour. Res. 50, 4585–4602.

Kemmerly, P.R., 1976. Definitive doline characteristics in the Clarksville quadrangle, Tennessee. Geol. Soc. Am. Bull. 87, 42-46.

Lawrence, D.S., Allen, J.R.L., Havelock, G.M., 2004. Salt marsh morphodynamics: An investigation of tidal flows and marsh channel equilibrium. J. Coast. Res. 20, 301-316.

Levy, D.A., Northcote, T.G., 1982. Juvenile salmon residency in a marsh area of the Fraser River estuary. Can. J. Fish. Aquat. Sci., 39, 270– 276.

Mandelbrot, B., 1983. The Fractal Geometry of Nature. W.H Freeman, New York, NY.

Mark, D.M., Church, M., 1977. On the misuse of regression in earth science. Math. Geol. 9, 63-75.

Myrick, R.M., Leopold, L.B., 1963. Hydraulic geometry of a small tidal estuary. Geol. Survey Prof. Paper 422-B.

Novakowski, K.I., Torres, R., Gardner, L.R., et al., 2004. Geomorphic analysis of tidal creek networks. Water Resour. Res. 40, W05401, doi:10.1029/2003WR002722.

Odum, W.E., 1984. Dual-gradient concept of detritus transport and processing in estuaries. Bull. Mar. Sci., 35, 510– 521.

Ogden, J.C., Davis, S.M., Jacobs, K.J., et al., 2005. The use of conceptual ecological models to guide ecosystem restoration in South Florida. Wetlands 25, 795-809.

Ouchi, S., Matsushita, M., 1992. Measurement of self-affinity on surfaces as a trial application of fractal geometry to landform analysis. Geomorphology 5, 115–130.

Rinaldo, A., Fagherazzi, S., Lanzoni, S., et al., 1999a. Tidal networks 2: Watershed delineation and comparative network morphology. Water Resour. Res. 35, 3905–3917.

Rinaldo, A., Fagherazzi, S., Lanzoni, S., et al., 1999b. Tidalnetworks 3: Landscape-forming discharges and studies in empirical geomorphic relationships. Water Resour. Res. 35, 3919–3929.

Rinaldo, A., Belluco, E., D'Alpaos, A., et al., 2004. Tidal networks: Form and function. In: Fagherazzi, S., Blum, L., Marani, M., (Eds.), Ecogeomorphology of Tidal Marshes. Am. Geophys. Union, Washington, D.C., pp. 75-91.

Rodriguez-Iturbe, I., Rinaldo, A., 1997. Fractal River Basins: Chance and Self-Organization. Cambridge Univ. Press, New York, NY.

Roman, C.T., Burdick, D.M., 2012. Tidal Marsh Restoration: A Synthesis of Science and Management. Island Press, Washington, DC.

Rozas, L.P., McIvor, C.C., Odum, W.E., 1988. Intertidal rivulets and creekbanks: Corridors between tidal creeks and marshes. Mar. Ecol. Prog. Ser. 47, 303–307.

Sanderson, E.W., Ustin, S.L., Foin, T.C., 2000. The influence of tidal channels on the distribution of salt marsh plant species in Petaluma Marsh CA, USA. Plant Ecol. 146, 29–41.

Schmidt-Nielsen, K., 1984. Scaling: Why is Animal Size so Important? Cambridge University Press, Cambridge.

Sedell, J.R., Duval W.S., 1985. Water transportation and storage of logs. General Technical Report PNW-186. United States Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Shi, Z., Lamb, H.F., Collin, R.L., 1995. Geomorphic change of saltmarsh tidal creek networks in the Dyfi estuary, Wales. Marine Geol. 128**,** 73–83.

Simenstad, C.A., 1983. The Ecology of Estuarine Channels of the Pacific Northwest: A Community Profile. FWS/OBS-83/05. U.S. Fish and Wildlife Service, Washington, DC.

Simenstad, C., Tanner, C., Crandell, C., et al., 2005. Challenges of habitat restoration in a heavily urbanized estuary: Evaluating the investment. J. Coast. Res. SI 40, 6-23.

Smyth, A.R., Thompson, S.P., Siporin, K.N., et al., 2012. Assessing nitrogen dynamics throughout the estuarine landscape. Estuaries Coasts 36, 44-55.

Spencer, K.L., Harvey, G.L., 2012. Understanding system disturbance and ecosystem services in restored saltmarshes: Integrating physical and biogeochemical processes. Estuar. Coast. Shelf Sci. 106, 23-32.

Syvitski, J.P.M., 2008. Deltas at risk. Sustainability Sci. 3, 23-32.

Temmerman, S., Bouma, T.J., Govers, G., et al., 2005. Flow paths of water and sediment in a tidal marsh: Relations with marsh developmental stage and tidal inundation height. Estuaries 28, 338-352.

Tucker, M.A., Ord, T.J., Rogers, T.L., 2014. Evolutionary predictors of mammalian home range size: body mass, diet and the environment. Global Ecol. Biogeogr. 23, 1105-1114.

Van Maren, D.S., Van Kessel, T., Cronin, K., et al., 2015. The impact of channel deepening and dredging on estuarine sediment concentration. Continental Shelf Res. *95*, 1-14.

Williams, G.D., Zedler, J.B., 1999. Fish assemblage composition in constructed and natural tidal marshes of San Diego Bay: Relative influence of channel morphology and restoration history, Estuaries 72, 702–716.

Williams, P.B., Orr, M.K., Garrity, N.J., 2002. Hydraulic geometry: a geomorphic design tool for tidal marsh channel evolution in wetland restoration projects. Restor. Ecol. 10, 577–590.

Winterwerp, J.C., Wang, Z.B., van Braeckel, A., et al., 2013. Man-induced regime shifts in small estuaries—II: a comparison of rivers. Ocean Dynamics 63, 1293-1306.

Woldenberg, M.J., 1966. Horton's laws justified in terms of allometric growth and steady state in open systems. Geol. Soc. Am. Bull. 77, 431–434.

Wolinsky, M.A., Edmonds, D.A., Martin, J., et al., 2010. Delta allometry: Growth laws for river deltas. Geophys. Res. Lett. 37, L21403, doi:10.1029/2010GL044592.

Wolters, M., Garbutt, A., Bakker, J.P., 2005. Salt-marsh restoration: evaluating the success of de-embankments in north-west Europe. Biol. Conserv. 123, 249–268.

Yang, Z., Khangaonkar, T., Calvi, M., et al., 2010a. Simulation of cumulative effects of nearshore restoration projects on estuarine hydrodynamics. Ecolog. Model. 221, 969-977.

Yang, Z., Sobocinski, K.L., Heatwole, D., et al., 2010b. Hydrodynamic and ecological assessment of nearshore restoration: A modeling study. Ecol. Model. 221, 1043-1053.