Comparing channel form of restored tidal marshes to ancient marshes of the North San Francisco Bay

Meredith Hall

University of California at Berkeley

Paper submitted for LA222: Hydrology for Planners
Professor G. Matthias Kondolf
April 24, 2004

Abstract

In this study, I examine channel form in restored and natural tidal marshes to understand how marshes evolve from salt ponds and agricultural fields to naturally functioning tidal marshes. I examined the channel morphology of two marshes near the mouth of the Napa River in Solano County, California – one natural marsh approximately 100 years old ("centennial marsh") and one restored in 1995 – using mapping techniques in ArcView GIS. I followed the techniques of a previous analysis done by Phil Williams and Associates (PWA) in 2003 on four other restored and natural marshes in the North San Francisco Bay and examined channel sinuosity, bifurcation ratios, length ratios, and drainage density (Garrity 2003). By combining my results with the results of the other four marshes, I have found that the data no longer fully conforms with the trends found by PWA. Both studies found that bifurcation ratios and length ratios of first order channels tend to be larger for younger marshes. However, the contribution of my data shows that PWA's observation that drainage density decreases with age is not entirely true. Instead, with the addition of data from the Napa centennial marsh, drainage density conforms more closely with the findings of Steel and Pye (1997) that indicated drainage density increases with age up until about 150 years old and then decreases. Combining all of the data reveals that sinuosity tends to increase for 2nd order channels with the age of the marsh.

Introduction

When settlers and developers of the North San Francisco Bay turned the tidal marshes along the bay into agricultural and salt production sites, they altered a system of high biodiversity dependent on the regular disturbance of the tides. Dikes protecting salt ponds and farm fields cut the land off from the sediment deposition provided by the tides, eventually leading to subsidence of the land. When restoring these lands to marshes, project planners often must first deal with the problem of trying to restore land that is below sea level and cannot immediately support marsh vegetation. By opening dikes, sediment begins to replenish the subsided land, which then accumulates enough sediment for it to reach mean tide level, and marsh vegetation can reestablish and tidal channels can begin to form.

My study builds upon previous analyses run by Philip Williams and Associates on three restored sites and one natural site (table 1). PWA used this study to understand the process of marsh evolution in the North Bay. My study adds two more sites to this body of data, both near the mouth of the Napa River in the North San Francisco Bay (figure 1). Located between China Slough and South Slough, Pond 2a is a 550-acre former salt production pond now owned by the California Department of Fish and Game. It was first breached in 1995, when its elevation was three feet (ft). Over 40% of the pond was vegetated in 1995, and researches observed a full tidal range by October 1996 (Garrity and Orr 2003). The restoration of this pond has appeared to happen more quickly than other sites, perhaps because the marsh reestablished channels in line with the remnant ancient marsh channels (Stephen Crooks, personal communication, March 2004).

Table 1. PWA restored and reference marsh study sites. The "future studies" sites are those for which PWA has appropriate aerial photos to that they can analyze and add to this study.

Site Name	Location	Condition	Analysis
Pond 2A	Napa River	Restored (1995)	This study
White Slough	Napa River	Restored	Future studies
Napa centennial	Napa River	Centennial reference	This study
Ryer Island*	Suisun Bay	Restored	Future studies
Ryer Island*	Suisun Bay	Ancient reference	Future studies
China Camp	San Pablo Bay	Ancient reference	Future studies
Green Point	Petaluma River	Restored (1986)	PWA
Green Point	Petaluma River	Centennial reference	PWA
Carl's Marsh	Petaluma River	Restored (1994)	PWA
Petaluma ancient marsh	Petaluma River	Ancient reference	PWA

*at Ryer Island only part of the island was leveed and restored, so there is a natural reference area adjacent to the restored site

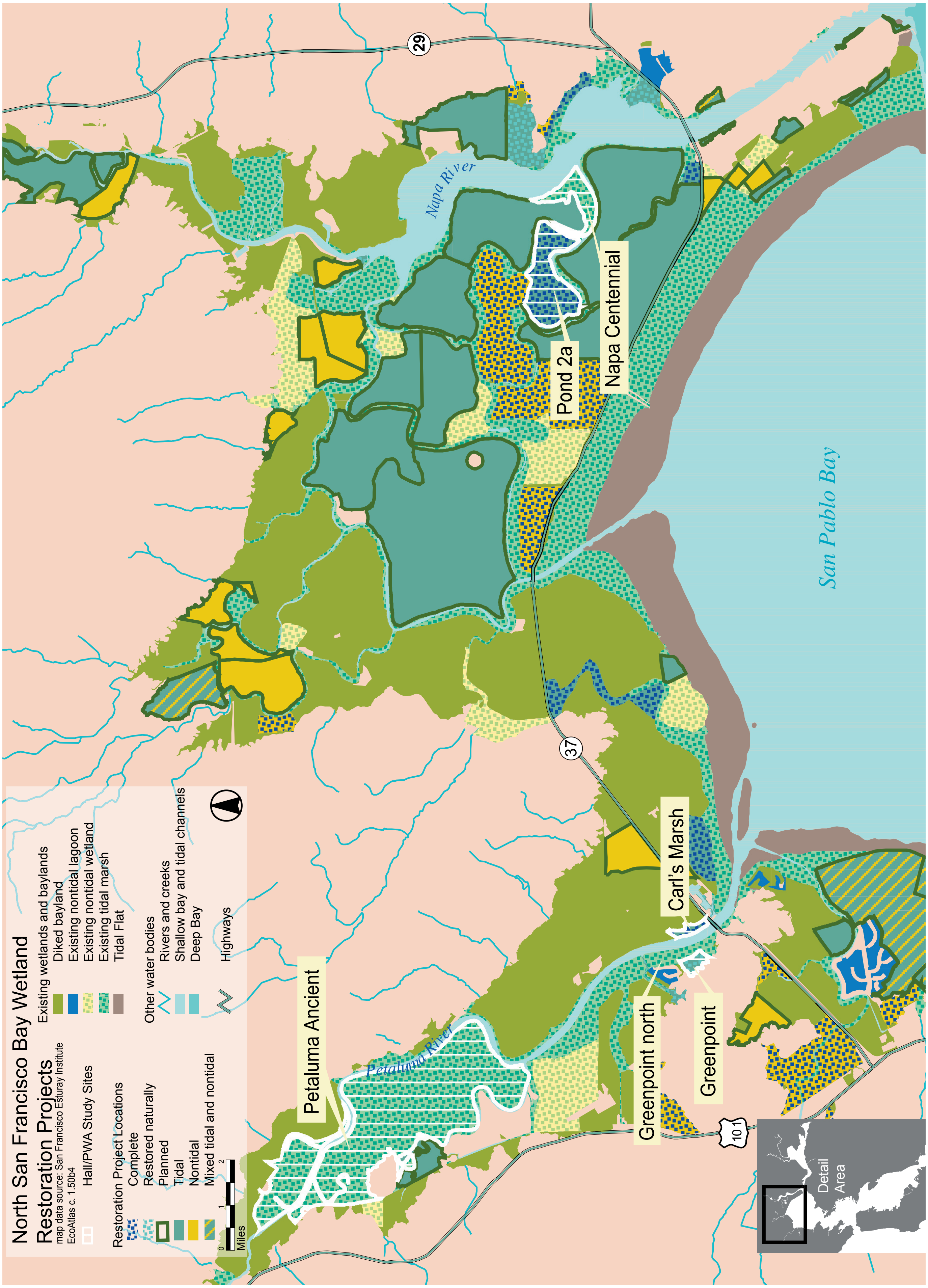


Figure 1. Location map of study sites within the North Bay restoration projects. I analyzed the channels of Pond 2a and Napa Centennial; PWA analyzed Petaluma Ancient, Greenpoint North, Greenpoint, and Carl's Marsh.

1.4 km to the southeast of Pond 2a, Napa centennial marsh lies at the junction of South Slough and the Napa River. There are two different sets of “reference” or “natural” marshes Phil Williams and Associates uses for comaparison with restored marshes. Ancient marshes are pre-settlement marshes (over 1000 years old), while centennial marshes formed in the past 100 years, as a result of hydraulic mining sending high sediment loads downstream (Garrity, personal communication, March 18, 2004).

Nick Garrity, Adam Parris, and Michelle Orr at Phil Williams and Associates recently performed channel morphometry analyses of several restored and reference marshes in the North Bay (see PWA sites in table 1). They found that with increased age, primary channel density decreases, the number and length of first order channels decreases relative to second order channels (bifurcation and length ratios), and channel sinuosity increases (Garrity and Orr 2003). By adding Pond 2a and Napa centennial marsh to this body of data, I can test the validity of these conclusions and further the understanding of marsh evolution in the North Bay.

Methods

Using ArcView3.2 GIS software and aerial photographs taken on September 29, 2003, I mapped channels on both marshes. For Pond 2a, I focused on the main channel flowing to China Slough (figure 2) on the advice of Stephen Crooks at PWA. On the Napa centennial marsh I focused on the channels whose entire drainages were visible in the photograph – those flowing into South Slough and a large channel just to the north of those, flowing into the Napa River (figure 3). I then categorized the order of each channel, used the extension XTools to calculate the channel length, and measured the “straight length” of each channel by hand using the measure tool (a less accurate mode of measurement than XTools). Finally, I mapped the drainage area and used XTools to calculate the area (see data in Appendix A).

Following the PWA analysis, I used several metrics to compare the restored and natural marshes. Channel sinuosity is the ratio of the length of the channel to the straight length (where the channel is defined as stream segments that do not cross another channel). Bifurcation ratio is the ratio of the number of stream segments in one order to the next (Pidwirny 2004), while length ratio is the total stream length in one order divided by the total stream length in the next. Drainage density is the ratio of the total channel lengths to the drainage area (Pidwirny 2004).

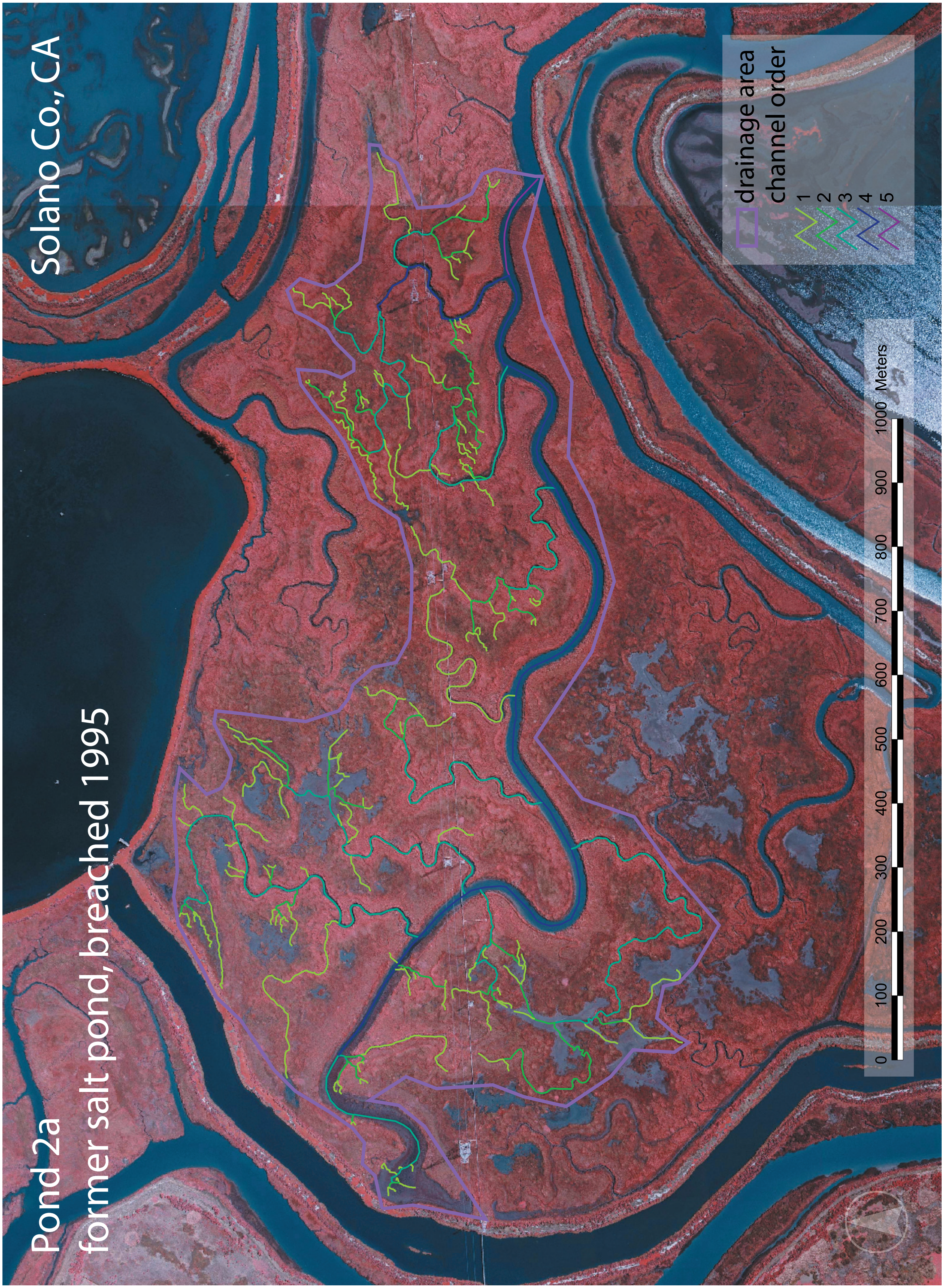


Figure 2. Channels of Pond 2a.

Figure 3. Channels of Napa Centennial Marsh.

Results

Table 2. Comparison of restored and centennial marshes in the North San Francisco Bay, by sinuosity, bifurcation ratio, length ratio, and drainage density. (* indicates that PWA calculated these figure using smaller drainages.)

Sinuosity (m/m)	Pond 2a (restored)	Carl's marsh (restored)	Greenpoint (restored)	Greenpoint north (centennial)	Napa centennial (natural)	Petaluma ancient (natural)
age	8	9	17	100	100	1000
all	1.30				1.21	
1st order	1.28	1.12*	1.19*	1.15*	1.24	1.72*
2nd order	1.33	1.15	1.23	1.23	1.22	1.44
3rd order	1.40	1.35	1.14	1.21	1.19	1.33
4th order	1.17	1.05	1.28		1.08	1.55
5th order	1.07	1.14	1.22			

bifurcation ratios (n/n-1)	Pond 2a (restored)	Carl's marsh (restored)	Greenpoint (restored)	Greenpoint north (centennial)	Napa centennial (natural)	Petaluma ancient (natural)
age	8	9	17	100	100	1000
1st order	2.18	3.38*	2.69*	1.43*	1.81	2.00*
2nd order	1.17	7.60	5.57	4.80	2.27	3.00
3rd order	3.12	2.50	2.33		4.33	2.00
4th order	17.00	2.00	3.00			

length ratio (m/m)	Pond 2a (restored)	Carl's marsh (restored)	Greenpoint (restored)	Greenpoint north (centennial)	Napa centennial (natural)	Petaluma ancient (natural)
age	8	9	17	100	100	1000
1st order	1.13	0.34*	0.33*	0.38*	0.82	0.11*
2nd order	0.53	0.34	0.73	0.84	0.69	0.52
3rd order	0.68	0.74	0.34		0.84	0.60
4th order	0.71	0.25	0.28			

drainage density (km/km^2)	Pond 2a (restored)	Carl's marsh (restored)	Greenpoint (restored)	Greenpoint north (centennial)	Napa centennial (natural)	Petaluma ancient (natural)
age	8	9	17	100	100	1000
	22.75192	25.46279	19.87991	26.86154	32.02501	16.28770

Discussion

The addition of data from Pond 2a and Napa centennial marsh confirmed the PWA conclusions for sinuosity, somewhat confirmed the conclusions for bifurcation and length ratios, and revealed another trend for drainage density.

With the addition of the two new sites, I have found that first and second order channel sinuosity generally conforms with PWA's conclusion that sinuosity increases with marsh age (figure 4). While Pond 2a seems to be an outlier in this case because its sinuosity is higher than all but the ancient marsh, this may not conflict with the trend. Pond 2a seems to behave, according to all the metrics, like an older marsh, which may be due to the fact that the new channels in the pond follow the form of the pre-settlement channels of the ancient marsh on the site.

Figure 4. Sinuosity ratios of first and second order marsh channels in the North San Francisco Bay. (Fit lines in figures 4-7 are approximate and for illustration only.)

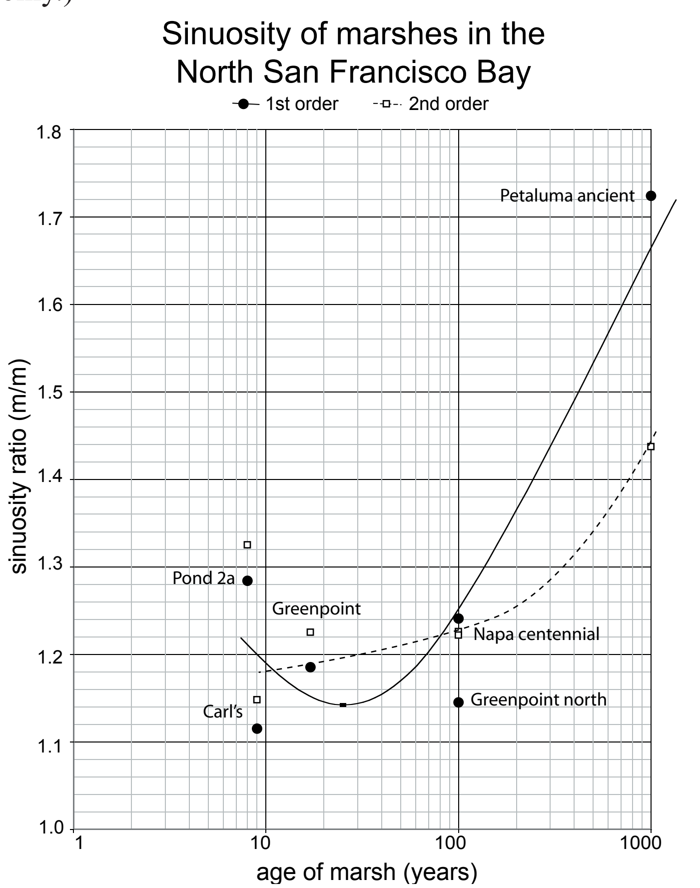


Figure 5. Bifurcation ratio by channel order of restored Pond 2a and Napa centennial marshes. (Channel order 2 indicates the number of first order channels divided by second order channels.)

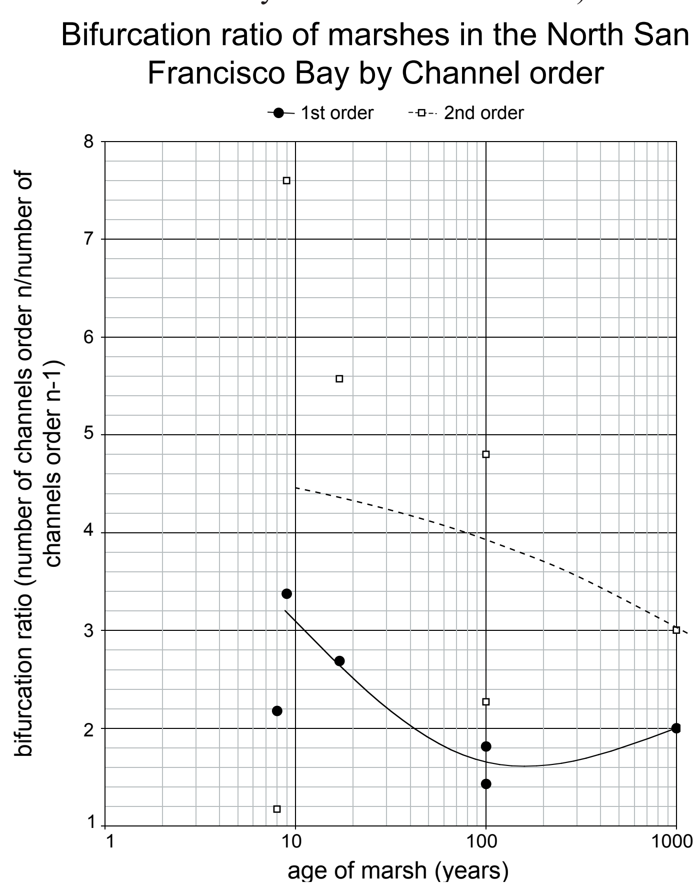


Figure 6. Channel length ratios by channel order of restored Pond 2a and Napa Centennial marshes.

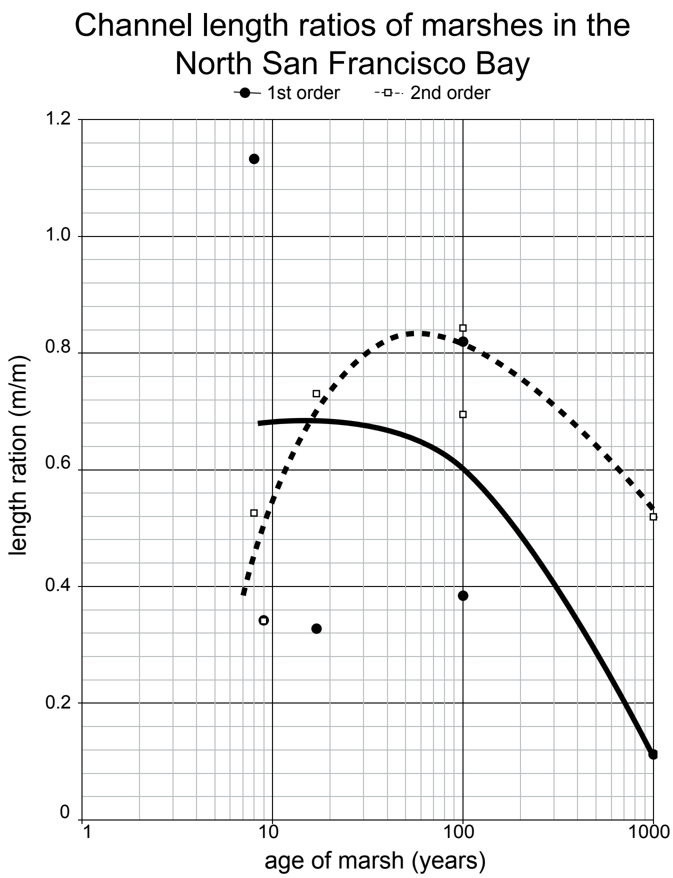
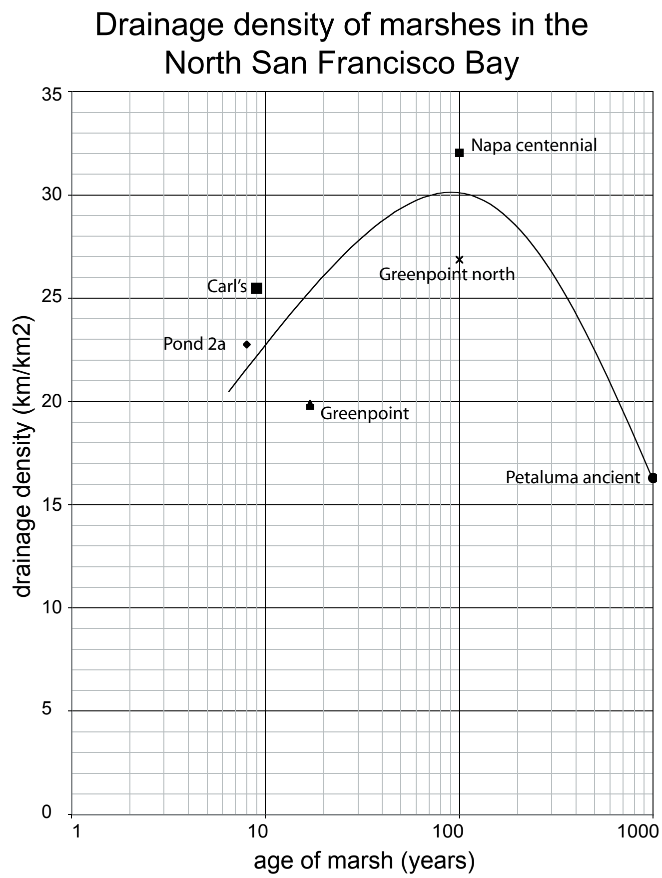


Figure 7. Drainage density.



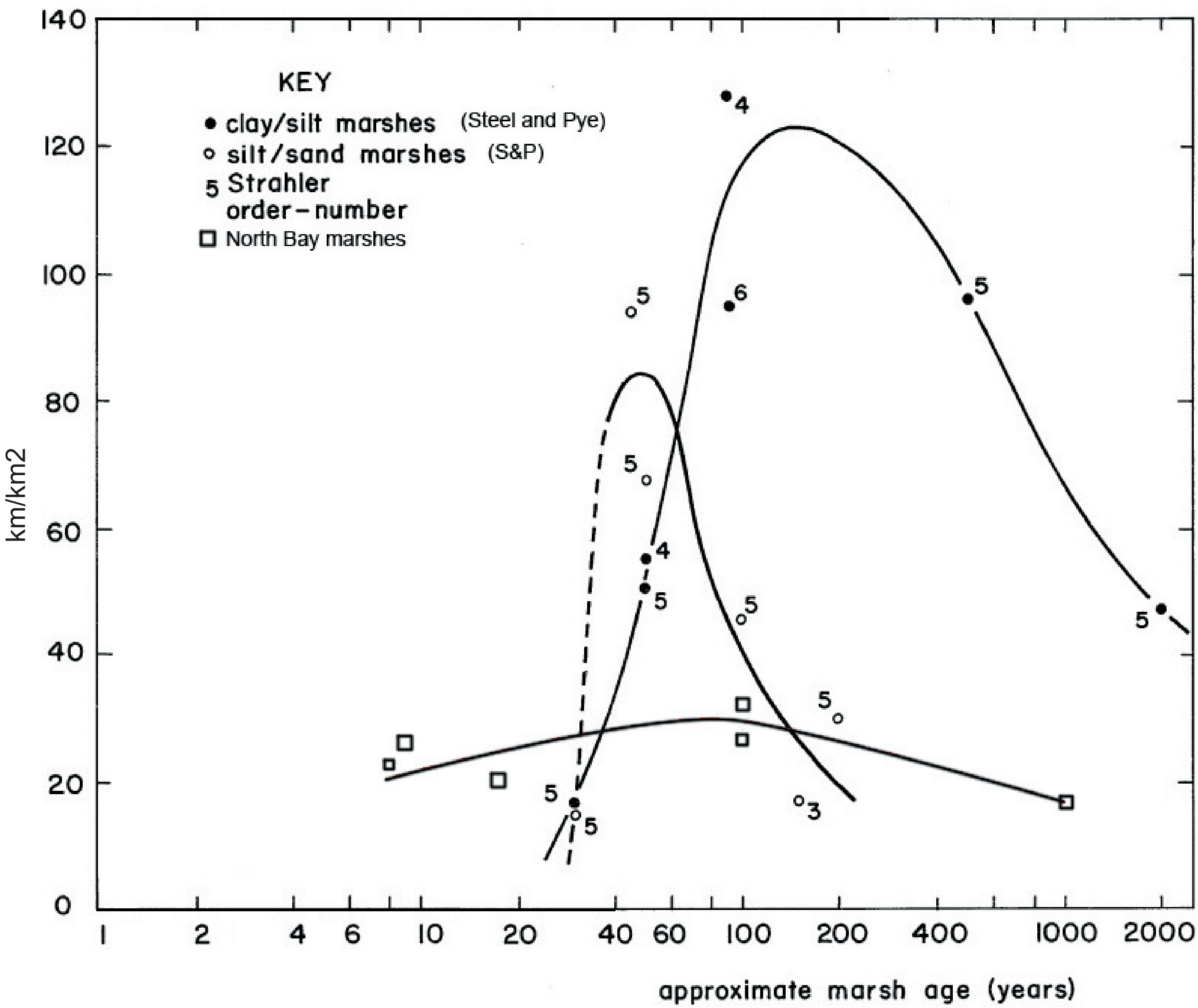
Bifurcation ratios of first order and second order channels were smaller in the older marshes than the restored marshes in the PWA study. The trend seems to hold with the addition of Pond 2a and Napa centennial, even more clearly when one considers Pond 2a as an older marsh (figure 5). PWA also found that length ratio of first/second order channels decreased with age of marsh. The addition of the two sites does not make this trend any clearer; the Pond 2a and Napa centennial marshes have first order length ratios at least twice that of the other four marshes (figure 6). This may be related to the nature of the data collection. While I measured the length of every channel in Pond 2a and Napa centennial, due to time constraints PWA chose smaller subdrainages as representative samples from which to measure the first order and second order lengths in the other marshes.

PWA found that drainage density decreases with age, while my comparison of drainage densities found that drainage density actually increases with age until at least 100 years (i.e. Napa centennial) and then decreases (figure 7). This conforms more with the trends found by Steel and Pye (1997) in English marshes.

Conclusions

The addition of the data from Pond 2a and Napa centennial reveals some small modifications to be made to PWA's earlier conclusions. It may also show that the restoration of Pond 2a is much further along than the restoration projects at other marshes. In J. R. L. Allen's (2000) review of the morphodynamics of marshes, a 1965 study done by Pestrong in the San Francisco Bay found that channels tend to be straighter when they are young and become more sinuous with age (Pestrong 1965). Pond 2a may be behaving like an older marsh because it has adopted the form it once had as a pre-settlement marsh. The marsh had also accumulated some vegetation and was already above sea level when the dike was breached in 1995, indicating that it may have been further developed than the other restored marshes in the study.

Figure 8. Steel and Pye's (1997) graph of tidal creek drainage density as a function of approximate marsh age in Britain overlayed with the North San Francisco Bay drainage density data.



Another study referred to by Allen (2000), Steel and Pye (1997), found that drainage density increased as marshes aged up to 150 years, and after that drainage density decreased with age (figure 8). In this study, the restored marshes are all less dense than the centennial marsh, in line with Steel and Pye's study, while the ancient marsh is the least dense, creating a similar curve for marshes of the North San Francisco Bay as Steel and Pye's for English marshes. The drainage density curves developed from the English marshes in Steel and Pye's study are much steeper than the curve create by the North Bay data. The range of drainage density for silt/clay marshes in their study was from about 15 to 130 km/km^2 and silt/sand marshes varied from about 15 to 95 km/km^2. In the North Bay, drainage density ranged from only 16 to 32 km/km^2 – a factor of two rather than a factor of six or nine. According to Allen, few studies explain what controls drainage density and because Steel and Pye analyzed so few sites, more marshes need to be examined to understand it (Allen 2000). By comparing the North Bay marshes to the English marshes, it appears that either the North Bay has even finer sediments than the English marshes or another factor is at play, like the size of the tidal frame.

This study contributes to the understanding of how marshes restore in the South San Francisco Bay. The trends it begins to reveal – increasing sinuosity, decreasing first order bifurcation, and peaking drainage density – will help restoration designers understand how quickly a pond restores in terms of channel morphology. Researchers may analyze the success of marsh restoration by looking at how quickly a young marsh begins to exhibit the characteristics of an older marsh. In the North San Francisco Bay, it appears that the drainage density of marshes peaks somewhere around 30 km/km^2 at about 100 year old and bifurcation ratio decreases by about half from 10 to 100 years old. Some additional analysis will further this understanding. Two more restored marshes (Ryer Island and White Slough) and two more ancient marshes (Ryer Island and China Camp) have photos that researchers can analyze using this same technique. Further analysis examining how each individual marsh evolves over time will also enrich this understanding, as each site has unique characteristics affecting its development.

Finally, the main goal of tidal marsh restoration is most often habitat creation and enhancement. This study provides an understanding of the physical form of restored marshes, but cannot alone describe the ability of the marshes to support the high biodiversity of natural tidal marshes. In order to understand a marsh as fully restored, researchers must combine geomorphologic data with ecological data.

References

Allen, J.R.L. 2000. Morphodynamics of Holocene salt marshes: a review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quaternary Science Reviews* 19:1155-1231.

Garrity, Nick. 2003. Memorandum, re: BREACH 2 Preliminary Channel Morphometry PWA Ref #: 1513." San Francisco, CA, December 10, 2003.

Garrity, Nick, and Michelle Orr. 2003. Technical Memorandum, BREACH 2: Identification and Screening of Study Sites in San Pablo and Suisun Bays, PWA Ref. # 1513. San Francisco, CA, May 14, 2003.

Pestrong, R. 1965. The development of drainage patterns in tidal marshes. *Stanford University Publications in Earth Science* 10:1-87 (in Allen 2000).

Pidwirny, Michael. 2004. *CHAPTER 10: Introduction to the Lithosphere (ab). Stream Morphometry* 2004 [cited April 19 2004]. Available from http://www.physicalgeography.net/fundamentals/10ab.html.

Steel, T.J., and K Pye. 1997. The development of saltmarsh tidal creek networks: Evidence from the U.K. Paper read at Canadian Coastal Conference (in Allen 2000).

Appendix

A. Measurement data from GIS analysis of marshes in the North San Francisco Bay.

location	order	sinuous length (m)	straight length (m)	number of channels	average length (m)	area (km^2)
Pond 2a (breached 1995; my analysis)	all	15643.90	12023.87	268	58.37	0.688
	1	6509.57	5068.86	135	48.22	
	2	2639.99	1992.29	62	42.58	
	3	4292.65	3063.55	53	80.99	
	4	2033.39	1742.61	17	119.61	
	5	168.30	156.56	1	168.30	
Carl's Marsh (breached 1994; PWA analysis)	all	2567.95				0.101
	1	289.27		49	5.90	
	2	1132.09	986.08	38	29.79	
	3	436.56	323.66	5	87.31	
	4	235.90	224.24	2	117.95	
	5	474.13	415.08	1	474.13	
Green point (breached 1986; PWA analysis)	all	5205.37				0.262
	1	0.00				
	2	1916.28	1563.93	39	49.14	
	3	470.92	412.39	7	67.27	
	4	601.68	468.48	3	200.56	
	5	709.88	582.78	1	709.88	
Green point north (natural centennial; PWA analysis)	all	6598.62				0.246
	1	0.00				
	2	5029.81	4102.30	24	209.58	
	3	1243.58	1029.92	5	248.72	
Napa centennial (natural; my analysis)	all	15035.86	12377.56	396	37.97	0.470
	1	6785.09	5468.39	214	31.71	
	2	4563.62	3735.23	118	38.67	
	3	2895.89	2438.31	52	55.69	
	4	791.26	735.63	12	65.94	

location	order	sinuous length (m)	straight length (m)	number of channels	average length (m)	area (km²)
	all	2274.11				0.140
Petaluma ancient (natural; PWA analysis)	1	0.00				
	2	993.04	690.98	6	165.51	
	3	637.64	480.06	2	318.82	
	4	529.13	341.07	1	529.13	

Small subdrainages

location	order	sinuous length (m)	straight length (m)	number of channels	average length (m)	area (km^2)
	1	54.56		27	2	0.019
Carl's marsh	2	47.24	42.37	8	6	
	1	138.99		43	3	0.045
Greenpoint	2	157.89	133.20	16	10	
	1	63.40		10	6	0.019
Greenpoint north	2	115.52	100.89	7	17	
	1	15.85		2	8	0.015
Petaluma ancient	2	70.41	40.84	1	70	