DEVELOPMENT OF MARSH HYDROGEOMORPHOLOGY AND MARSH VEGETATION WITHIN A SALT HAY FARM WETLAND RESTORATION SITE

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ABSTRACT

Salt hay farming along the New Jersey shoreline of the Delaware River Estuary eliminated normal daily tidal flows over thousands of acres of coastal marshes. These sites were high marshes vegetated mostly with *Spartina patens*, *Distichlis spicata*, and *Juncus gerardi*. They were diked to facilitate farming. The restoration plan called for the breaching of the perimeter dikes and the dredging of inlets and new channels to re-establish the hydraulic connection with the estuary. The restoration construction at a salt hay farm at Dennis Township was completed in the fall of 1996. The restoration site is located in the Delaware River Estuary and is approximately 600 acres.

The restoration design called for construction of the primary (largest) and secondary channels. Development of the tertiary and smaller channels was to be completed through natural processes. An end-point model was developed to assess hydrogeomorphic development of the restoration site. We chose to use a stream order analysis, originally developed for fluvial systems to evaluate the development of the site hydrogeomorphology because, in large complex systems, it is not practical to measure tidal elevations at the required spatial density to equivocally demonstrate whether the desired site hydroperiod has been obtained. To complete our assessment of channel and hydroperiod development, we adapted the traditional stream order analysis techniques to examine changes in tidal channel morphology within the restoration site. Our modification of the system presents a new approach, which simplifies monitoring and evaluating hydrogeomorphologic development at large complex sites.

Establishment of site hydrogeomorphology is important but must be accompanied by the establishment of desirable marsh vegetation for restoration to be successful. Data are presented to show that the development of favorable vegetation within the site occurred rapidly. The project design called for limited marsh grass planting. However, natural re-vegetation occurred so quickly that it was unnecessary to plant marsh grasses within the restoration site. This marsh restoration project has been determined to be successful using the two key indicators of hydrogeomorphology and natural revegetation of the marsh plain.

Site Description

The Dennis Township Salt Hay Farm Wetland restoration site covers approximately 578 acres of wetland and is located in Dennis Township, Cape May County, NJ (Figure 1).

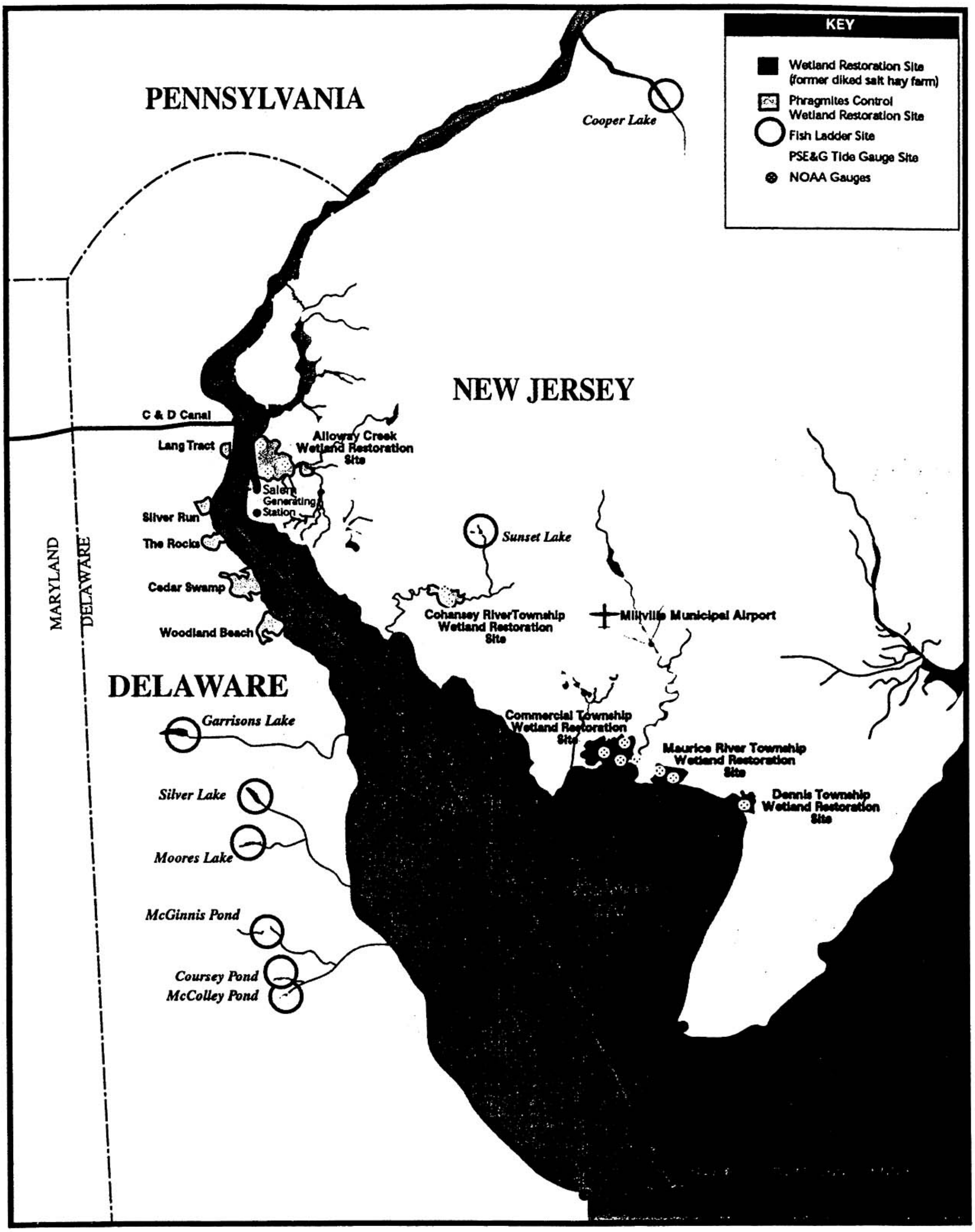

Figure 1. Location diagram.

The restoration area (369 acres) is bordered by West Creek on the west, the West Creek Gun Club on the north, East Creek on the east, and the Delaware Estuary on the south. Perimeter dikes were built around this area during the 1950's, eliminating normal tidal inundation over the entire site. During the 1980s, salt hay farming was abandoned on an approximately 195-acre area located in the northeast portion of the site. Much of the remaining acreage continued to be farmed for salt hay until acquired as a wetland restoration site in 1995. The diked salt hay farms were isolated from tidal flow and were in the process of becoming dominated by *Phragmites*. A detailed discussion is presented in Weishar et al., 1996 and 1997. The restoration objectives at this site were to restore tidal inundation, restore the natural high and low marsh mosaic, and reduce *Phragmites* coverage. With the completion of restoration construction in August 1996, the entire restoration area receives normal daily tidal inundation and drainage.

Background

A marsh restoration intuitively seems a worthwhile project. However, many times competing interests require more than a casual justification for restoring a marsh ecosystem. We embarked upon the marsh restoration project because the marsh ecosystem is a dynamic and changing environment with an intricate interaction of biological and physical processes that had been significantly degraded by the elimination of tides and the invasion of *Phragmites*. Tidal waters bring sediments, nutrients, and seeds into the marsh, and export detritus and other marsh by-products into the adjoining waters. Fish and other aquatic organisms travel up the tidal channels into the higher marsh with the tide to forage, returning with the ebbing tide to deeper channels and the Estuary. Tidal salt marshes provide essential links between coastal lands and estuarine waters (Childers and Day 1991; Mitsch and Gosselink 1993). Salt marshes provide foraging, breeding, nursery and refuge areas for aquatic and terrestrial animals, including many commercially important fish and shellfish species. Many fishes, for example, live in the open estuary, feeding at times on the marsh edge and traveling higher into the marsh via the tidal channels to forage (Hoss and Thayer 1993; Mitsch and Gosselink 1993; Fell et al. 1998). Vegetative characteristics of the marsh plain are associated with tidal inundation and drainage patterns, geomorphology, and salinity.

The three main components of the marsh ecosystem include tidal channels, marsh plains, and ponds/pannes. Tidal channels provide drainage pathways within the marsh, transporting nutrients, organisms, sediment, and other materials between the marsh and adjacent Estuary over the course of tidal cycles. Additionally, these channels provide the pathway for tidal waters to flow onto and off of the marsh plain, which, in turn, controls the marsh plain hydroperiod.

The vegetation on marsh plains contribute primary productivity and detritus to the open waters of the estuary and serves as habitat for birds and other terrestrial organisms. Vegetation also enhances sediment deposition, dampens wave energy, slows water velocity, and stabilizes the marsh plain (Kraeuter 1976; Edwards and Frey 1977). Plant roots also enhance sediment porosity, permeability, aeration, water percolation, and chemical diffusion (Frey and Basan 1985). Open water, in the form of ponds or pannes, is retained at low tide and is essential habitat for aquatic fishes and macroinvertebrates.

Importance of Marsh Plain Hydroperiods

The inundation and drainage of the marsh plain during the normal tidal cycle is one of the most critical processes within the marsh system. The wetting duration of the marsh plain surface by tides is termed the hydroperiod. Tidal activity generally determines the upper and lower extent of vegetation in the marsh. The lower vegetation limit is set by processes such as the depth and duration of tidal flooding, the mechanical effects of waves, sediment availability, and erosional forces (Chapman 1960), and the ability of the higher plants to survive periods of immersion. The upper limit of marsh vegetation (high marsh) usually extends to the limit of flooding on extreme tides (Beeftink 1977). High marsh usually extends to the limit of flooding on extreme tides.

Tidal inundation has physical and chemical effects on marshes. Flooding of the marsh plain raises pore water levels, decreases oxygen diffusion, and increases soil saturation (Mitsch and Gosselink 1993). When the marsh plain is covered by tidal waters, chemical transformations occur, which, in turn, affect the biogenic processes. Some of these transformations include a shift from oxic to anoxic conditions; increased pH; organic nitrogen transformation to ammonia; and a shift from oxidized to reduced forms of iron, manganese, and sulfur (sulfide). All of these processes have a dramatic effect on the wetland biological community.

Tides carry sediments from the estuary to marshes. They also serve to physically transport nutrients and organic matter to and from marshes (Hellings and Gallagher 1992). Tidal flooding exposes plants to mechanical wave energy. Soil aeration, chemistry, and salinity are altered by tidal flooding and subsequently, control plant growth. Additionally, the amount of open water area, sediment type, and density of tidal channels all have an affect on the hydroperiod of the marsh plain.

The relationship between the establishment of hydroperiod and growth of marsh plain vegetation is well understood; however, little data exists that quantifies this relationship. Seneca et al. (1985) examined the long-term relationship between growth of *Spartina spp.* and invasive plant species and hydroperiod. They found that a hydroperiod of 4 hours or less was favorable for the growth of *Phragmites* and other invasive non-*Spartina* species. Their study showed that *Spartina spp.* would grow on a marsh plain that was inundated for up to 12 hours per day, while development of *Phragmites* and other invasive species was impeded by this hydroperiod. The optimum hydroperiod, which resulted in the largest standing crop for marsh plain re-vegetation, was in the 3-hour range during the first 3 years after planting. After the 5^{th} growing season, however, the conditions, which supported the maximum standing crop, shifted from a 3-hour to an 11-hour hydroperiod.

“Top Down” Channel Order Analysis

We incorporated Ecological Engineering (Mitsch, 1996) into the design for this restoration. Only the primary and secondary marsh channels were constructed. The design depended upon natural processes to develop the tertiary and smaller streams (Weishar et al. 1996, 1997, and 1998). Therefore, we needed to quantify the development of the tertiary and smaller channels across the marsh plain.

We initially selected the classic stream order analysis of Horton (1945) because it had proven successful in restoring riparian streams. Horton (1945) emphasized topographic characteristics of the drainage area and gave a hierarchical order to every channel in the drainage basin. With this analysis, he was able to establish relationships between river order and lengths of courses (channels) between river order and size of the respective drainage basin, as well as the number of streams of a certain order. The Horton method is a "top-down" approach that relied on determining the order of the central drainage channel (Fig. 2), which is then carried through the entire drainage area. The Horton method becomes subjective when the drainage area is highly bifurcated or has several branches that are nearly equal in length and number of branches. Horton later attempted to quantified this technique (Chow, 1964) however, the initial stream channel layout was still highly subjective

Strahler (1957; 1964) modified this system by starting the next highest order at the confluence of two tributaries of lower order (Fig. 3). This eliminated the need to trace one of the central streams back to its source through the entire drainage basin. Strahler’s method is based on the premise that, for a sufficiently large sample size, order number is directly proportional to relative watershed dimensions, channel size, and volume of stream discharge. Also, because the order number is a dimensionless value, two drainage basins of different sizes can be compared at corresponding points through the use of order numbers.

The stream/channel order analysis was completed for both the restoration site and the reference marsh. Two hydrogeomorphic comparisons were made using the channel order analysis. A comparison of the number of channels within each channel order was made for the restoration site and the reference marsh. The number of channels per class is defined as the summation of all channels within a class across the entire drainage area. For the reference marshes and restoration sites, the total area was used as the drainage area. A measurement of the total number of channels is useful when comparing sites of similar size. However, one cannot assess the site hydrogeomorphology of two different sized sites using only the total number of channels within each channel class.

To address this limitation, two additional hydrogeomorphic comparisons were made: channel frequency and channel sinuosity. The channel frequency (F_C) is defined as the average number of channels of all orders (N_T) per unit area (A_B) of the drainage basin:

$$F_C = N_T/A_B$$

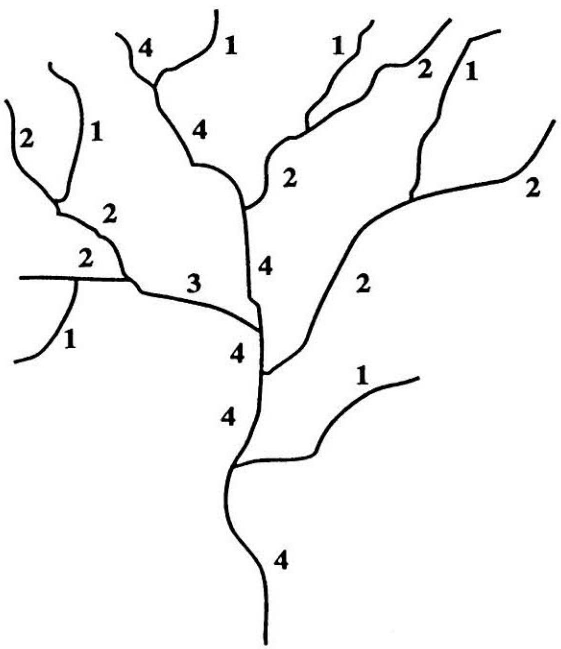

Figure 2. Horton Stream Order Technique (1954).

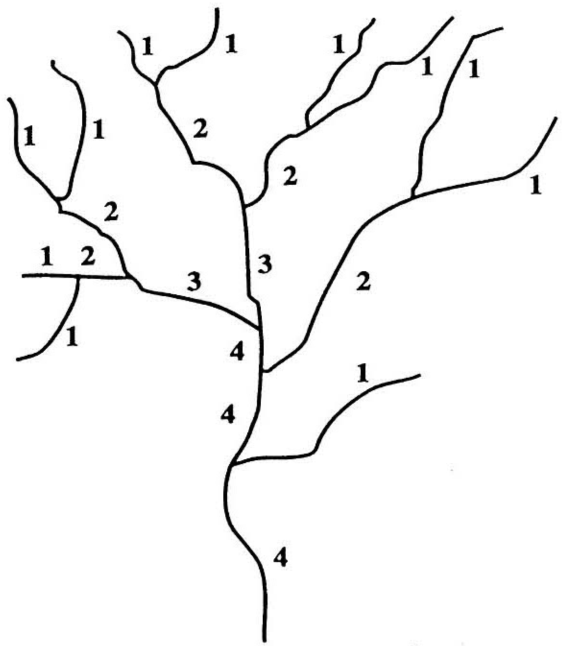

Figure 3. Channel order of analysis after Strahler (1957).

Channel frequency is a measurement of channel density. This measurement can be viewed as a normalized number of channels and is a measure of hydraulic efficiency, which can be used to compare different sized sites. When comparing a small site with a larger site, the smaller site often has a smaller number of channels, but a larger channel frequency. As a result, the smaller site will have a greater hydraulic efficiency than the larger site.

RESULTS

Channel frequency and order at Dennis Township are shown in Figure 4. The Dennis Township restoration site was opened to tidal flow in August 1996 following excavation of the large primary and secondary channels as reflected in the September 1996 data (Figure 4).

Use of Ecological Engineering in the design left the tertiary and smaller channels to form naturally over time. This is reflected in the increase in channel orders from three to four (Figure 4). The largest channel density increase is inversely correlated with the size of the channel. This is expected because as the system begins to evolve, new channels form on the channel margins of the large, dredged primary and secondary channels. Channel density was calculated beginning in 1997 because immediately after the site was opened channel densities would have not been representative of the evolving marsh.

The channel order analysis is a nondimensional analysis. The large dredged channels in the traditional ordering have the highest (largest number) order. To compare the changes that occurred at Dennis Township during the first year after restoration, the 1996 data were shifted so that the largest orders could be directly compared (Figure 5). Several inconsistencies are apparent. There were thirty-one 2nd and 3rd order (shown as 4th and 5th on Figure 5) channels in 1996 (Table 1). In 1997 our analysis shows there are only 7 4th and 5th order channels. If we include the 3rd order channels in this sum it increase only to 25. This means that we have lost 7 of the largest channels identified and mapped in 1996. These results prompted a re-examination of the assumptions and methodologies used by Horton and Strahler.

Table 1
Number of Marsh Channels

Channel Order	Number of Channels (1996)	Number of Channels (1997)
1	65	216
2	26	53
3	5	18
4	0	6
5	0	1

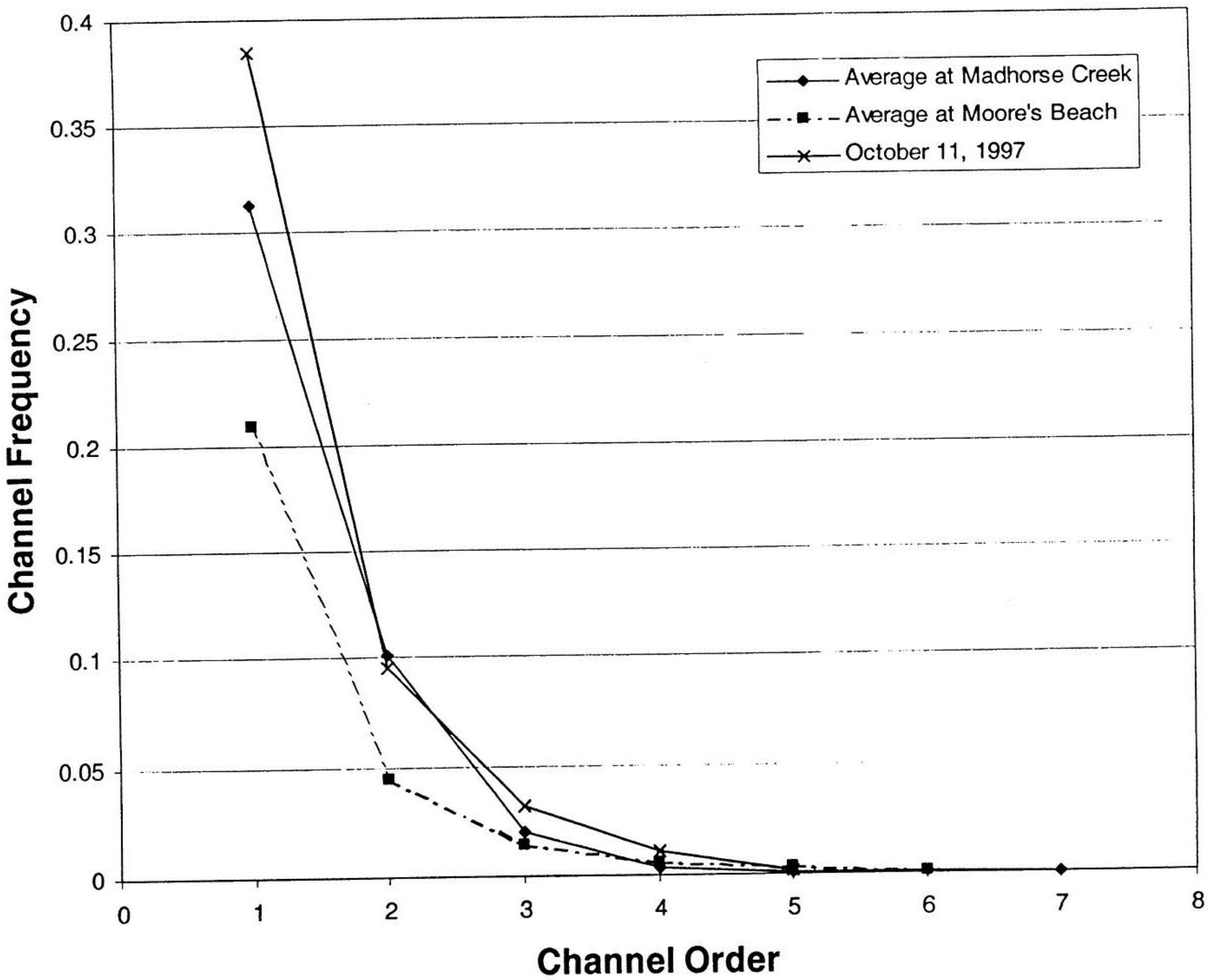

Figure 4. Channel frequency for the "top down analysis" at the Dennis Township site.

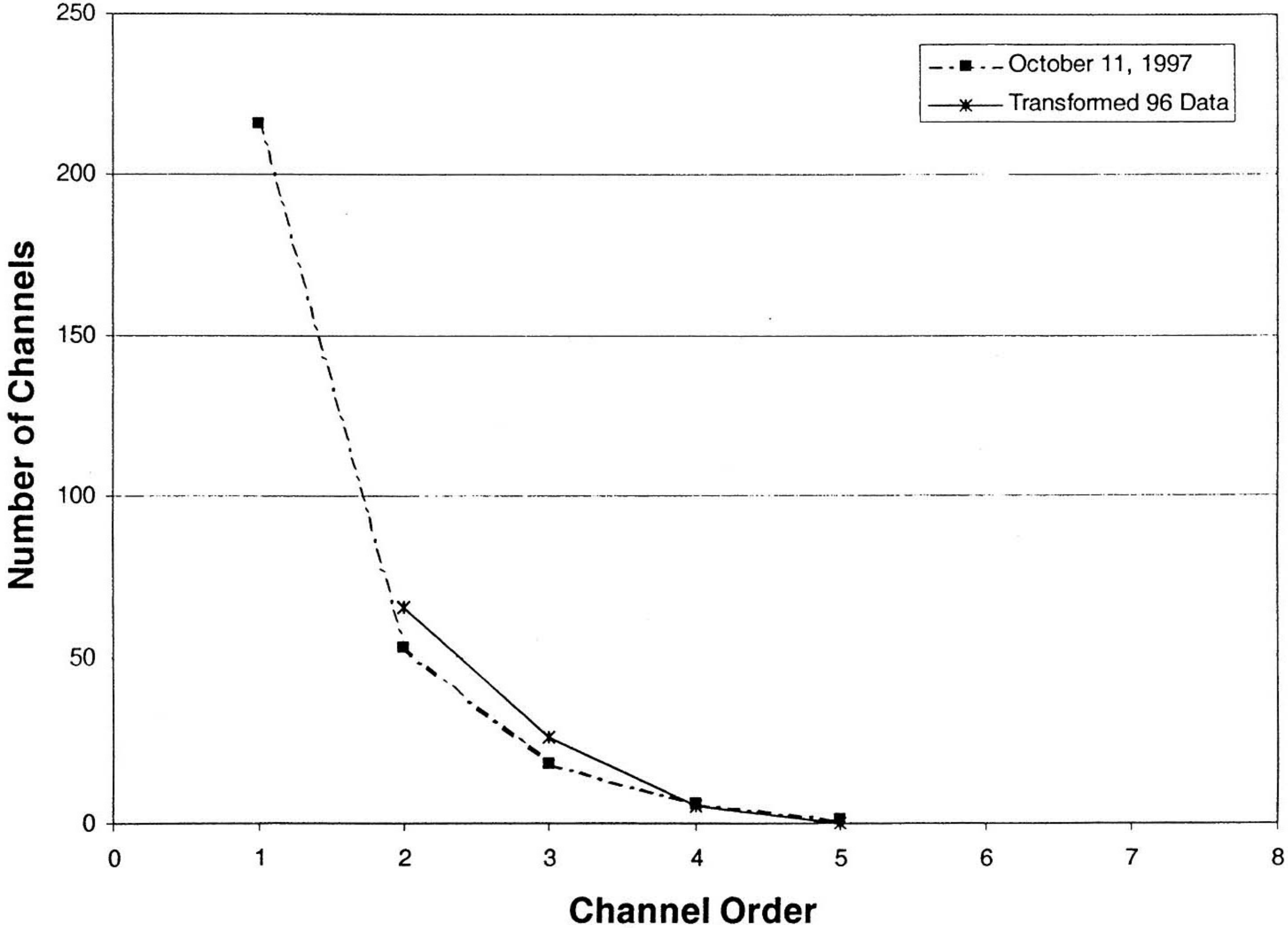

Figure 5. Transformed number of channels ("top down analysis) at the Dennis Township site.

These analytical stream geomorphology tools were developed for mature stream systems. An implicit assumption of order analysis is that a comparison of any two-channel orders should compare streams of comparable size. These techniques do not work well for rapidly developing salt marsh stream channels. The increasing the number of small channels dramatically changes the order number of the largest channels (Figure 5). These changes in order, especially when summed across the restoration site, make it impossible to identify a channel dimension with a channel order.

"Bottom-Up" Channel Order Analysis

To correct the problems associated with application of the "top-down" channel order approach, the hydrogeomorphic analysis technique was modified to be more useful for a dynamic system. All sites were re-analyzed using a "bottom-up" hydrogeomorphologic channel class analysis. A comparison of these two techniques is shown in Figures 6 and 7. Using this hydrogeomorphic "bottom-up" technique ensures that the largest channels are always the lowest order (1^{st} order) and that increasing order numbers are assigned to the rapidly changing smaller channels.

We reanalyzed the data from Moores Beach and the Dennis Township restoration site ordering channels using the "bottom up" channel ordering technique. Figure 8 shows the increase in the number of channels at the Dennis Township marsh restoration site for the years 1996, 1997, and 1998, and the number of channels at the two reference marshes Moores Beach and Mad Horse Creek. The rapid increase in the number of order 3 through 9 (smaller) channels over the three-year period is apparent. The "bottom-up" channel order analysis anchors our large channels and shows that the distribution and number of channels by channel class is beginning to approximate the reference marshes.

Figure 9 shows the channel frequency for the Dennis Township restoration site analyzed using the "bottom-up" technique for 1996, 1997, and 1998. This figure shows a rapid increase in the channel frequency. The distribution of channel classes at the wetlands restoration site is similar for both of the reference marshes. In fact, between 1997 and 1998 the channel frequency at Dennis Township surpassed the Moores Beach reference marsh and was rapidly approaching the channel frequency at the Mad Horse Creek reference marsh. The "bottom-up" channel order analysis shows the rapid increase in channel formation and provides a tool for adaptive managers to track the development of the frequency distribution of channel development over time. It also provides a tool to monitor the evolution of channel formation in restored marshes in comparison to the reference marshes.

Changes in Marsh Plain Vegetation

Our design for the marsh restoration was predicated on the hypothesis that if the proper hydraulic conditions were established, the marsh would revegetate naturally from the seeds deposited on the marsh plain from adjacent marshes. Additionally, the reduction and elimination of *Phragmites* would occur as a result of the re-introduction of relatively

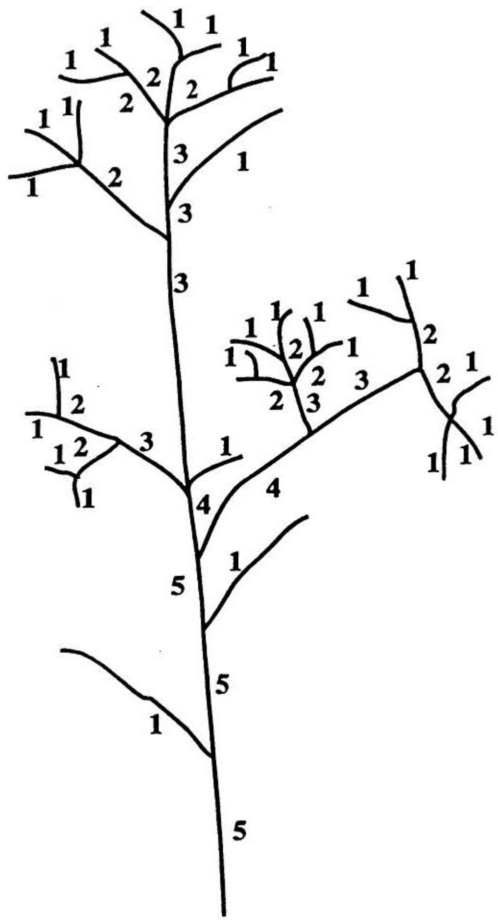

Figure 6. "Top Down" stream oder convention.

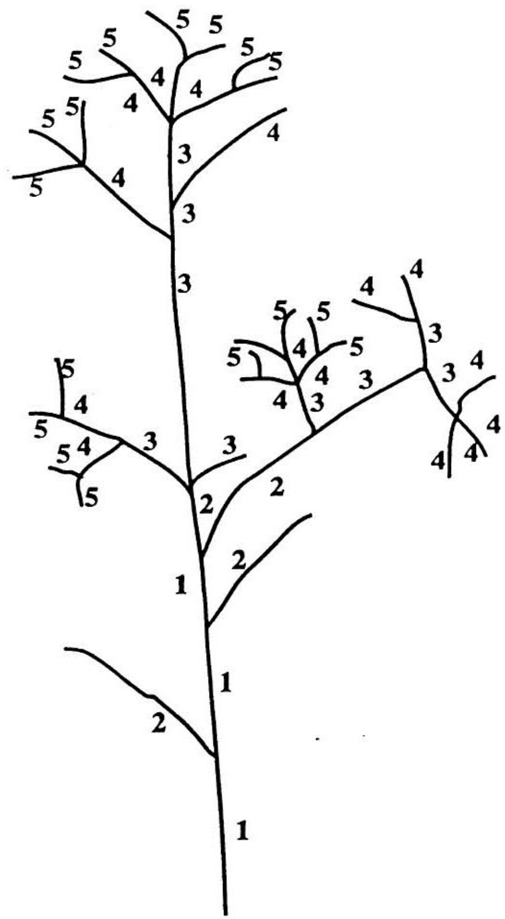

Figure 7. "Bottom Up" stream oder convention.

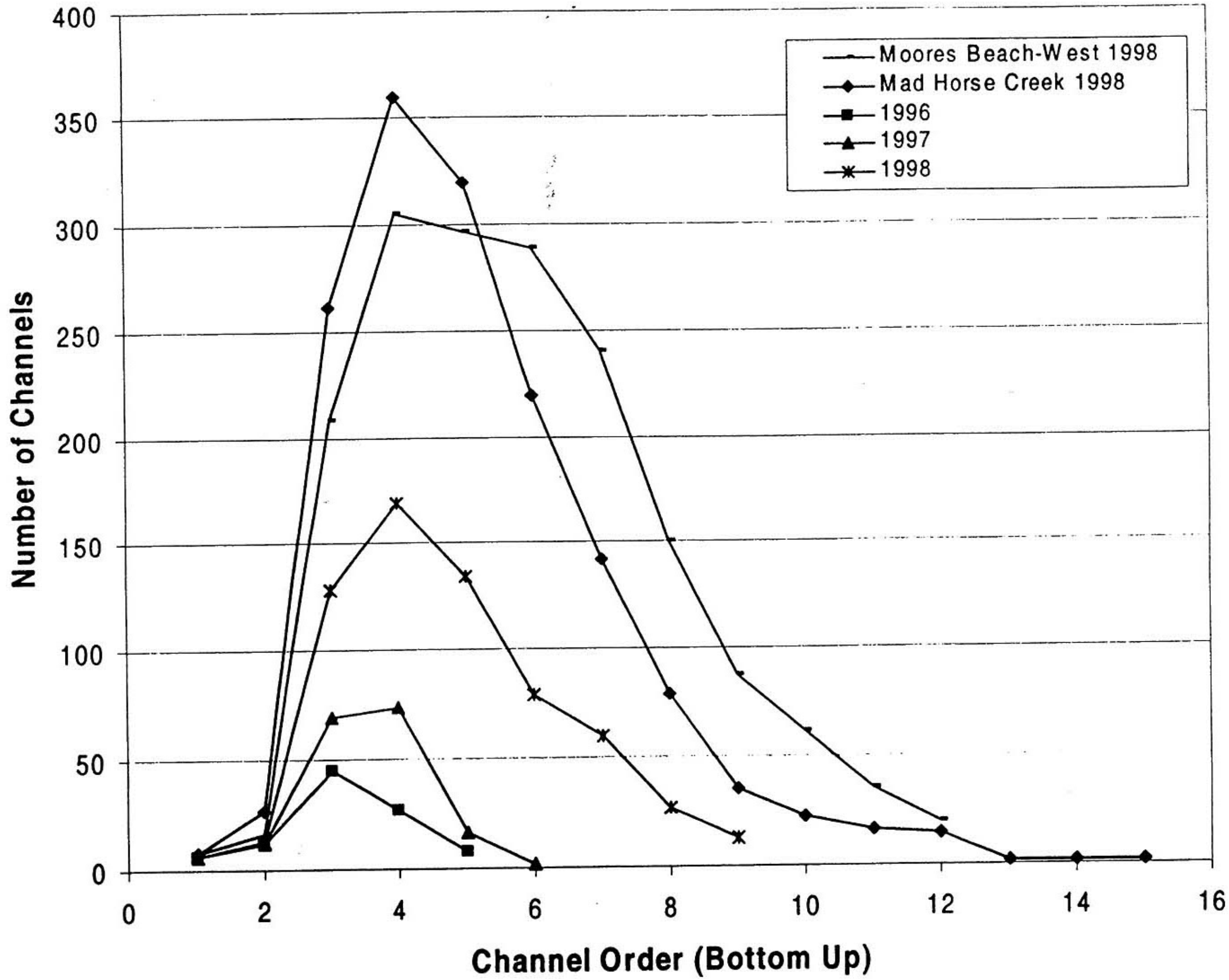

Figure 8. Number of channels for the "bottom up" analysis at the Dennis Township site.

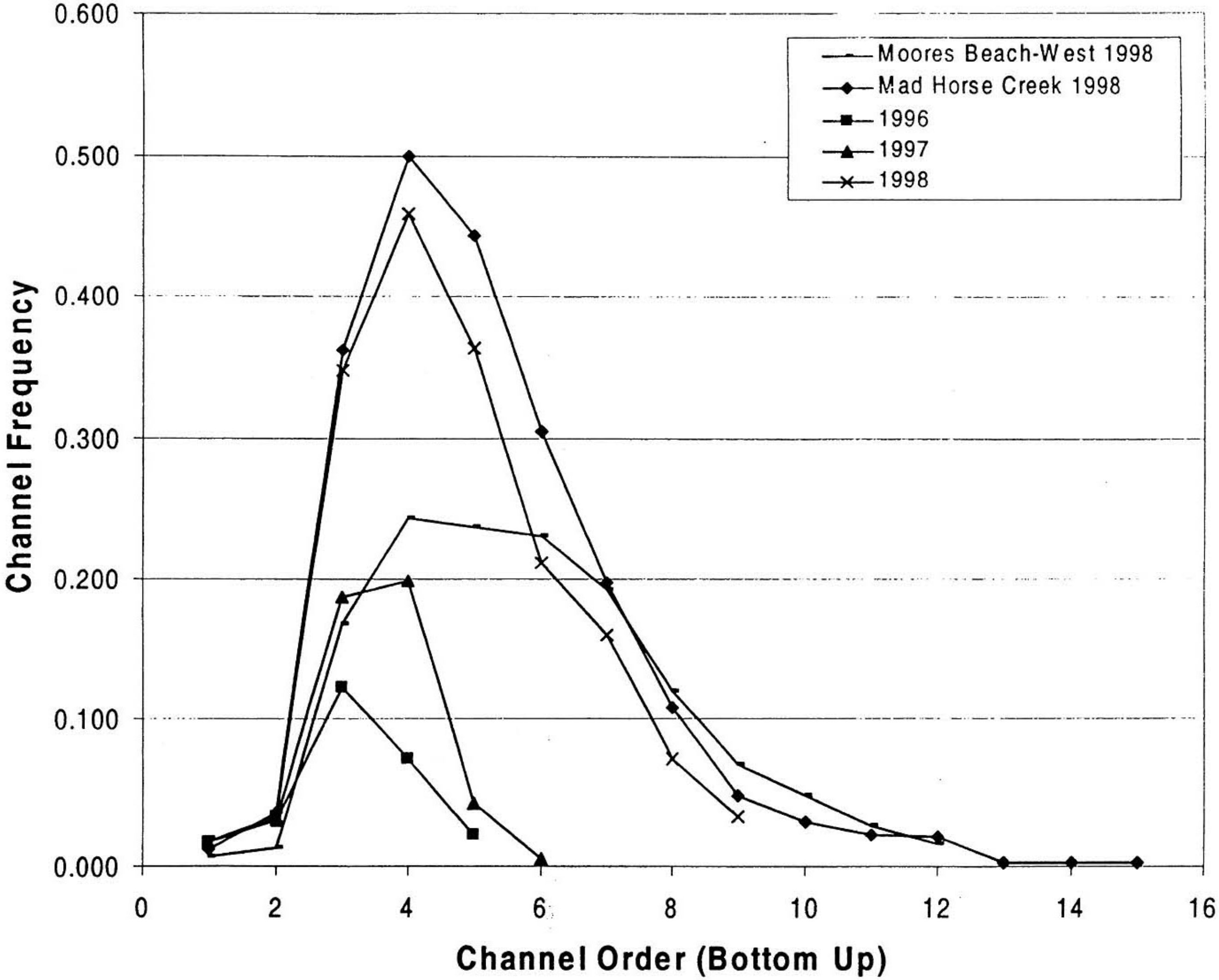

Figure 9. Channel frequency for the "bottom up" analysis at the Dennis Township site.

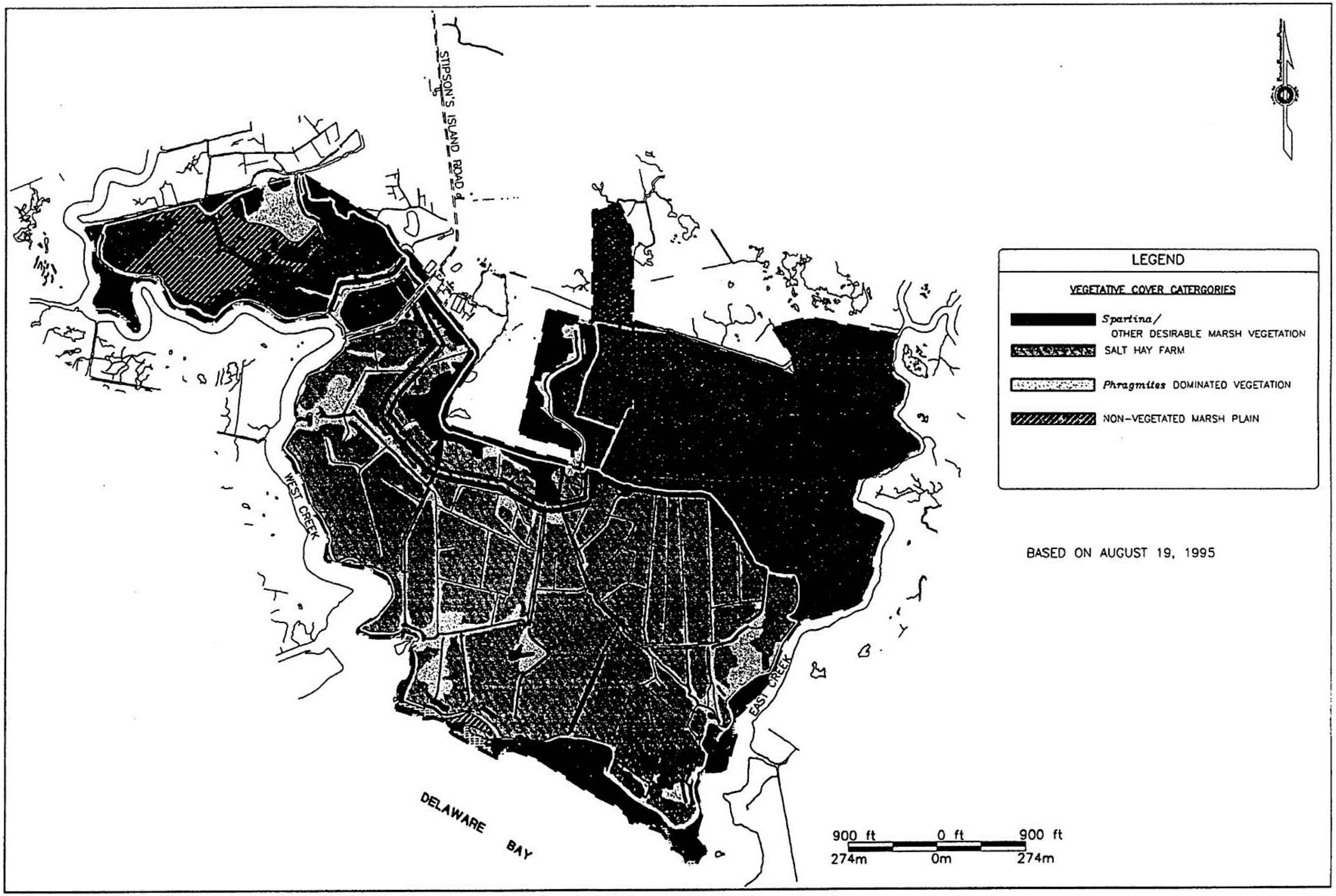

Figure 10. Pre-restoration conditions at the Dennis Township site.

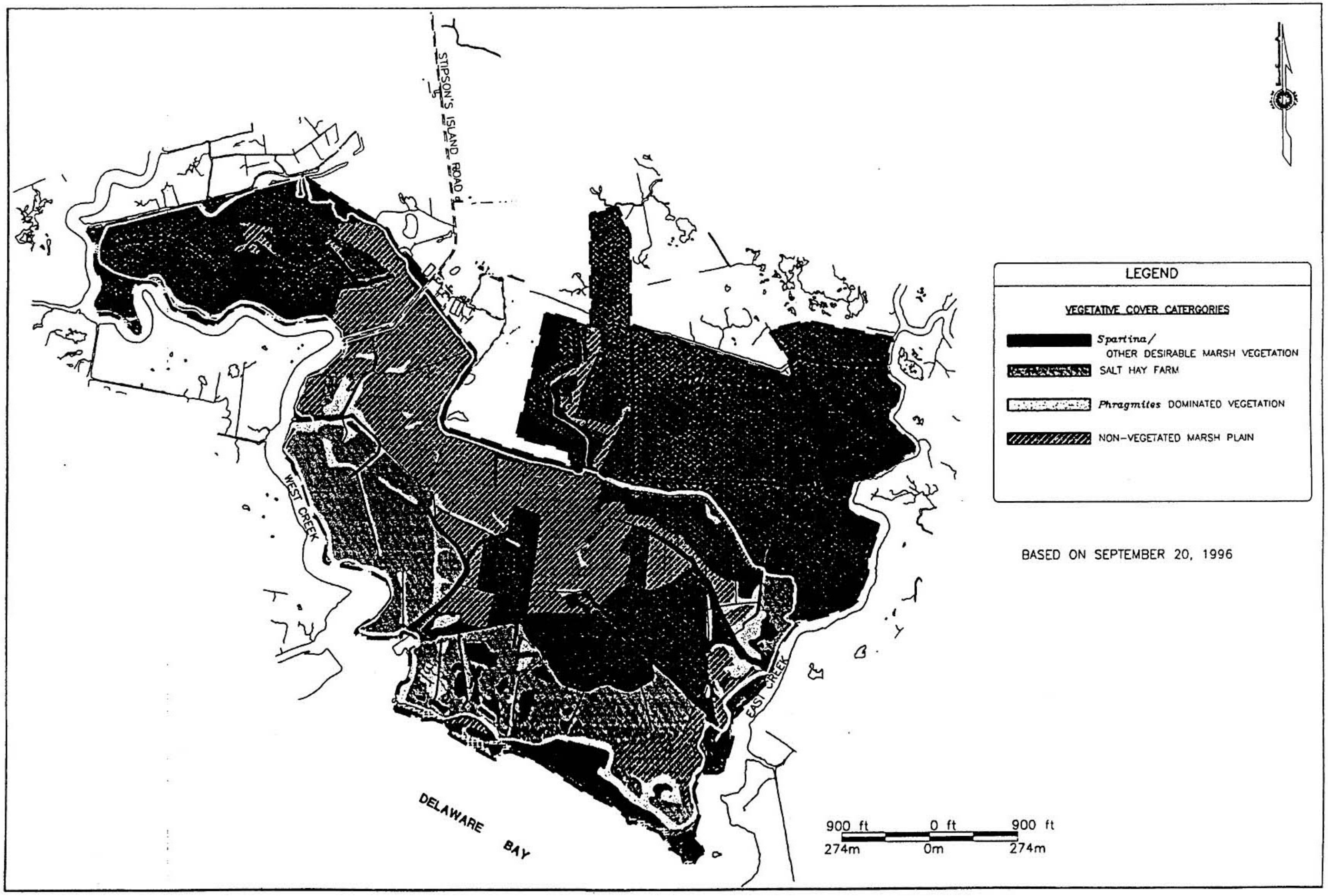

Figure 11. Vegetation mapping after the 1996 growing season at the Dennis Township site.

high salinity tidal waters to the site. The restoration design did not call for the complete elimination of *Phragmites* from the site. It will still occur along the upland boarder and provide a valuable edge for wildlife. However, our goal was to eliminate monotypic stands *Phragmites* from the marsh plain.

The vegetation conditions that existed at the site prior to the restoration are shown in Figure 10. There were several large areas of open water, extensive salt hay fields, and areas of *Phragmites*. The open water areas were due to a pre-existing dike breach at the site. The salt hay fields are within the perimeter dikes of the salt hay farm. Figure 11 shows the site after construction of the primary and secondary channels and the opening of the dikes. The most notable differences between Figures 10 and 11 are the increases in the open water areas, *Spartina alterniflora*, and a corresponding decrease in *Spartina patens*.

During the three years between 1996 and 1998, the channels increased in number and size. The result was the establishment of a favorable hydroperiod. Tidal velocities on the marsh plain were low enough to encourage sedimentation and the deposition of seeds. Figure 12 shows the marsh plain vegetation at the end of the 1998-growing season. There has been an increase in open water areas and a dramatic increase *Spartina alterniflora*. The increase in open water areas are the result of herbivory from snow geese and the die-off of *Spartina patens*. Visual observations during the 1999 growing season have shown that these areas are now vegetated with *Spartina alterniflora*.

CONCLUSIONS

A hydroperiod favorable for the growth of *Spartina spp.* and other desirable, naturally occurring marsh vegetation has been established at the Dennis Township restoration site. The establishment of favorable hydroperiods provided low velocities within the tidal channels and favorable conditions for sediment and seed deposition on the marsh plain. Following the completion of restoration activities in 1996, monitoring indicated increased areas of mud flats and shallow ponded water. By the end of 1997, areas previously vegetated with salt hay (*Spartina patens*) were covered with new sediment and *S. alterniflora* seeds, which established stands of *Spartina alterniflora*. By 1998, monitoring data indicated that *Spartina alterniflora* had increased from 42.1 percent coverage in 1996 to 77.8 percent in 1998. The extent of *Phragmites* coverage has been reduced and much of the *Phragmites* that remains at the site is stunted from daily inundation of saline tidal waters. Mud flats and unvegetated marsh plain declined from nearly 32.6 percent in 1996 to 11.8 percent in 1998. This restoration at this site has been successful. The tidal flows have been re-established and the marsh plain has re-vegetated with *Spartina alterniflora* and other desirable marsh plants. The open water areas are decreasing in size and now are at a level equivalent to that in the natural marsh mosaic.

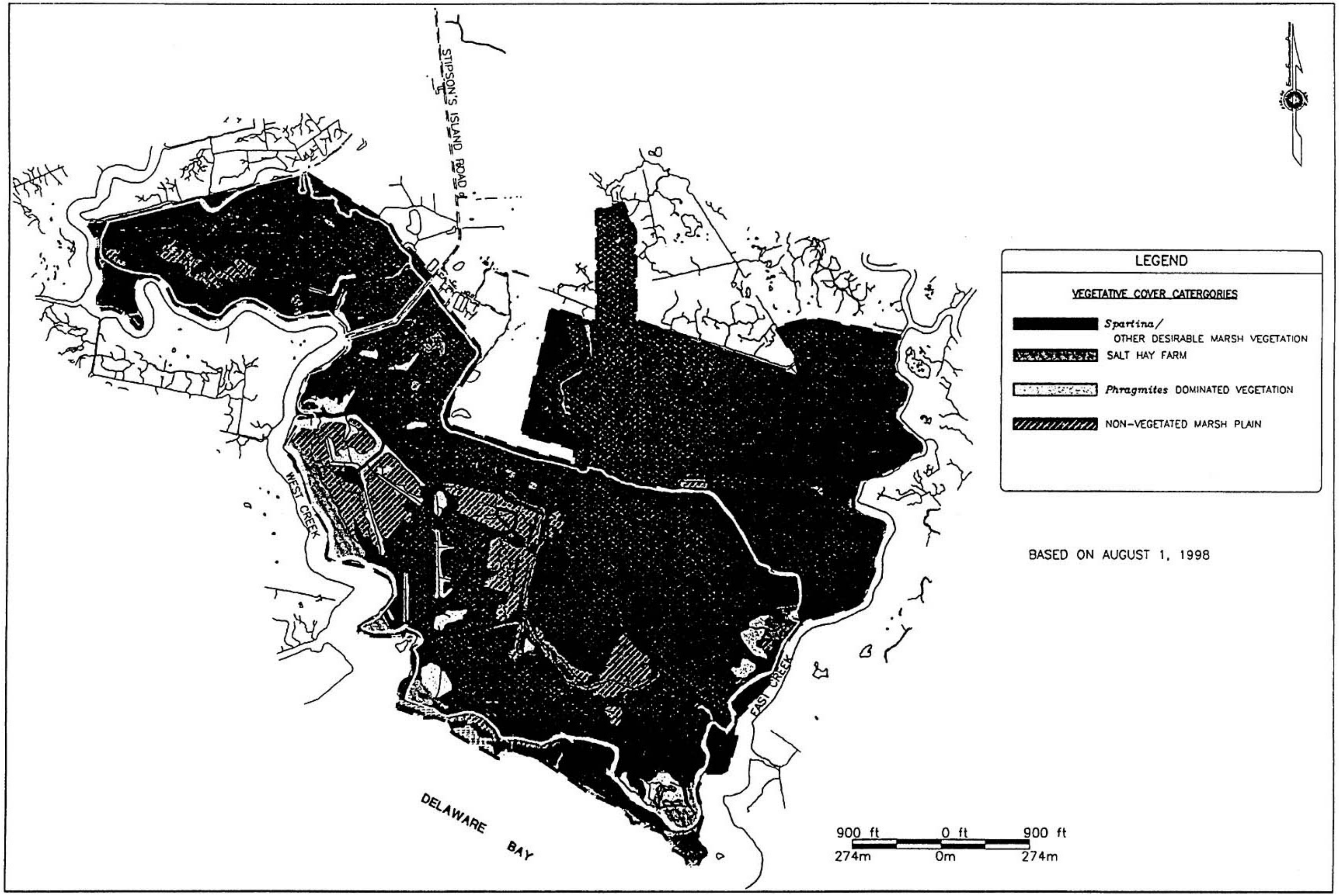

Figure 12. Vegetation mapping after the 1998 growing season at the Dennis Township site.

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