BATHYMETRIC ANALYSIS OF TILLAMOOK BAY

Comparison Among Bathymetric Databases
Collected in 1867, 1957 and 1995

by

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1. Background and Introduction

Several studies of sedimentation and sediment composition have been conducted in Tillamook Bay (e.g., Avolio 1973, Glenn 1978, Komar 1997). The latter report provides an overview of what is known about sedimentation of the bay, which is an important environmental concern because of its influence on habitat quality and navigation. Bathymetric surveys were conducted in 1867, 1957, and 1994/1995. E&S performed a comparative analysis for TBNEP of the available historical bathymetric data sets for the bay. The objective of this analysis was to quantify, to the extent possible, the changes in bathymetry that occurred between the times of the available surveys. It is considered likely that the bay has received excessive contributions of sediment since the last century. Major sources include:

- the breach of Bayocean Spit between 1952 and 1956
- deforestation in the watershed
- the Tillamook Burns of 1933, 1939, 1945, and 1951
- land use practices in the watershed, including road construction, agriculture, and urbanization

The greatest impacts of these sources of sedimentation probably occurred prior to the 1957 bathymetric survey.

In addition, the bay has been altered in a variety of other ways that have undoubtedly affected its bathymetry. These include the drainage of wetlands and construction of dikes and levees. The inlet from the ocean was modified by constructing jetties, and dredging of navigation channels has occurred throughout this century (Percy et al. 1974).

The most catastrophic change occurred in 1952 when the spit was breached just north of the current location of Cape Meares Lake. This may have been due to erosion of Bayocean spit in response to construction of the north jetty. The breach remained open until a dike was constructed in 1956 to close it off.

Three GIS coverages exist for the bay: 1867, 1957 and 1995. Below is a brief description of each data set.

2. Bathymetric Databases

1867 Bathymetric Data/Map

Bathymetric points collected in the 1867 survey were obtained from the U.S. Coast Survey Office. Data were derived from a paper map prepared by the U.S. Army Corps of Engineers. The coverage has 3750 points situated in an irregular network distributed throughout the bay and spaced approximately 200 to 300 m apart (Figure 1a). We noted that the x and y positional accuracy of the 1867 coverage appeared to have a shift when the outline of the bay was compared with the current bay outline (Figure 2). This was corrected using an affine coordinate transformation on twenty points located at locations presumed to be relatively stable on the shoreline of the bay. This transformation accounted for variability in scale, skewness, rotation and translation. The Root Mean Square Error of the transformation was 152 meters. The RMS error indicates how well the transformation matched the bay outline for all 20 data points across both data sets. It is a least square solution for the entire coverage. Several of the selected control points (i.e., Crab Harbor and one near McCoys Cove) may not have been as stable as we would like for this transformation. Excluding these points would only reduce the RMS error slightly. The transformed data set was used in the subsequent comparative analyses.

The 1867 coverage also illustrated many landscape features which were not present in the 1957 and 1995 coverages due to revetment and other changes to the bay shoreline. Cape Meares Lake, Garibaldi, McCoys Cove, Larson Cove and the Jetty changed in the time period between 1867 and the more recent surveys due to construction activities and the spit breach. These areas were digitized and a new bay boundary coverage was prepared.

1957 Bathymetric Data/Map

Bathymetric points for 1957 were derived from a U.S. National Oceanic Survey. Data were obtained from digital files that included 6,553 points. The data had been collected along transects across the bay with additional sampling in the major channels (Figure 1b). The data transects were generally spaced about 800 to 1000 m apart with sampling every 150 m.

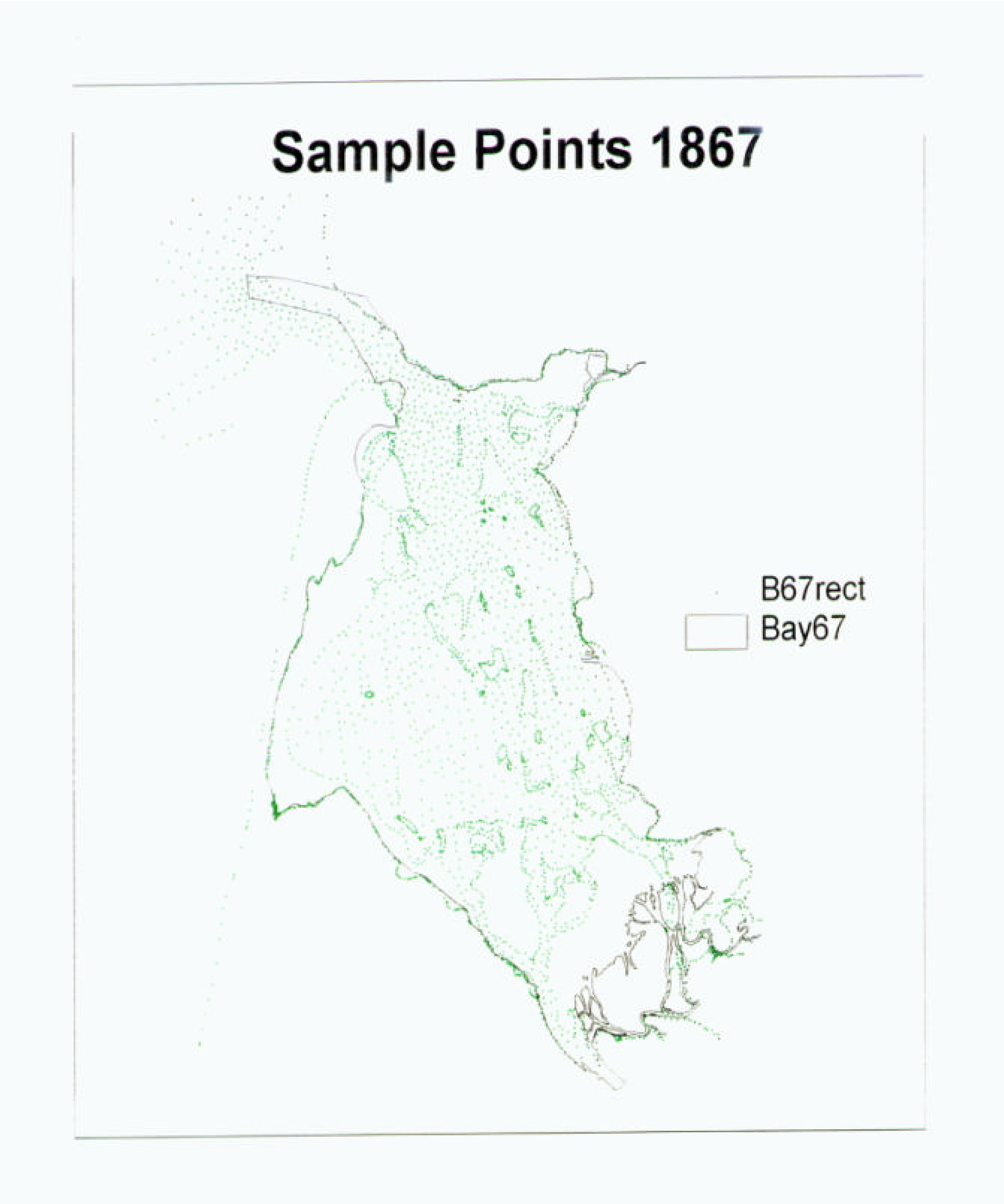

Figure 1a. Location of bathymetric data points derived from surveys conducted in 1857.

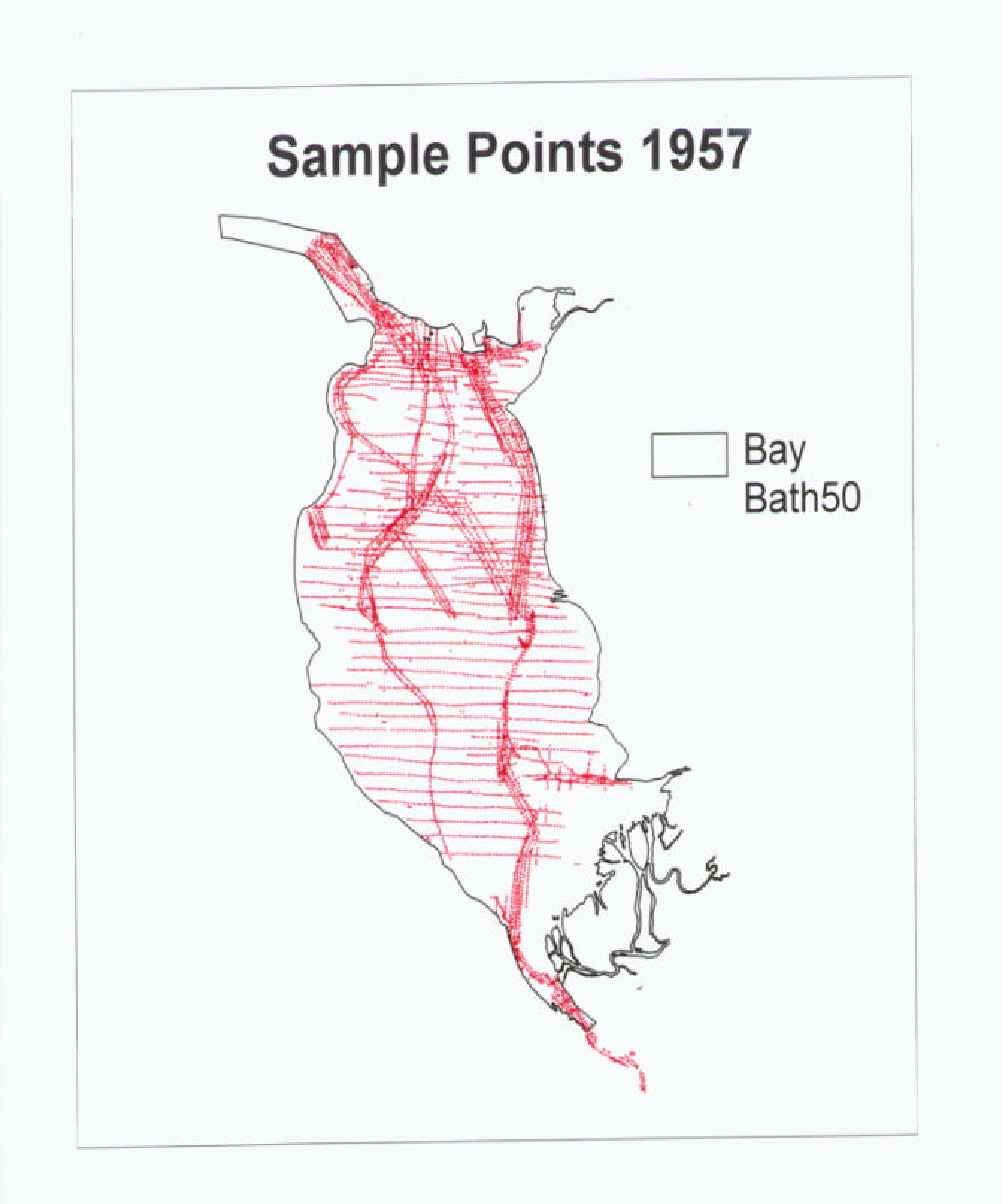

Figure 1b. Location of bathymetric data points derived from surveys conducted in 1957.

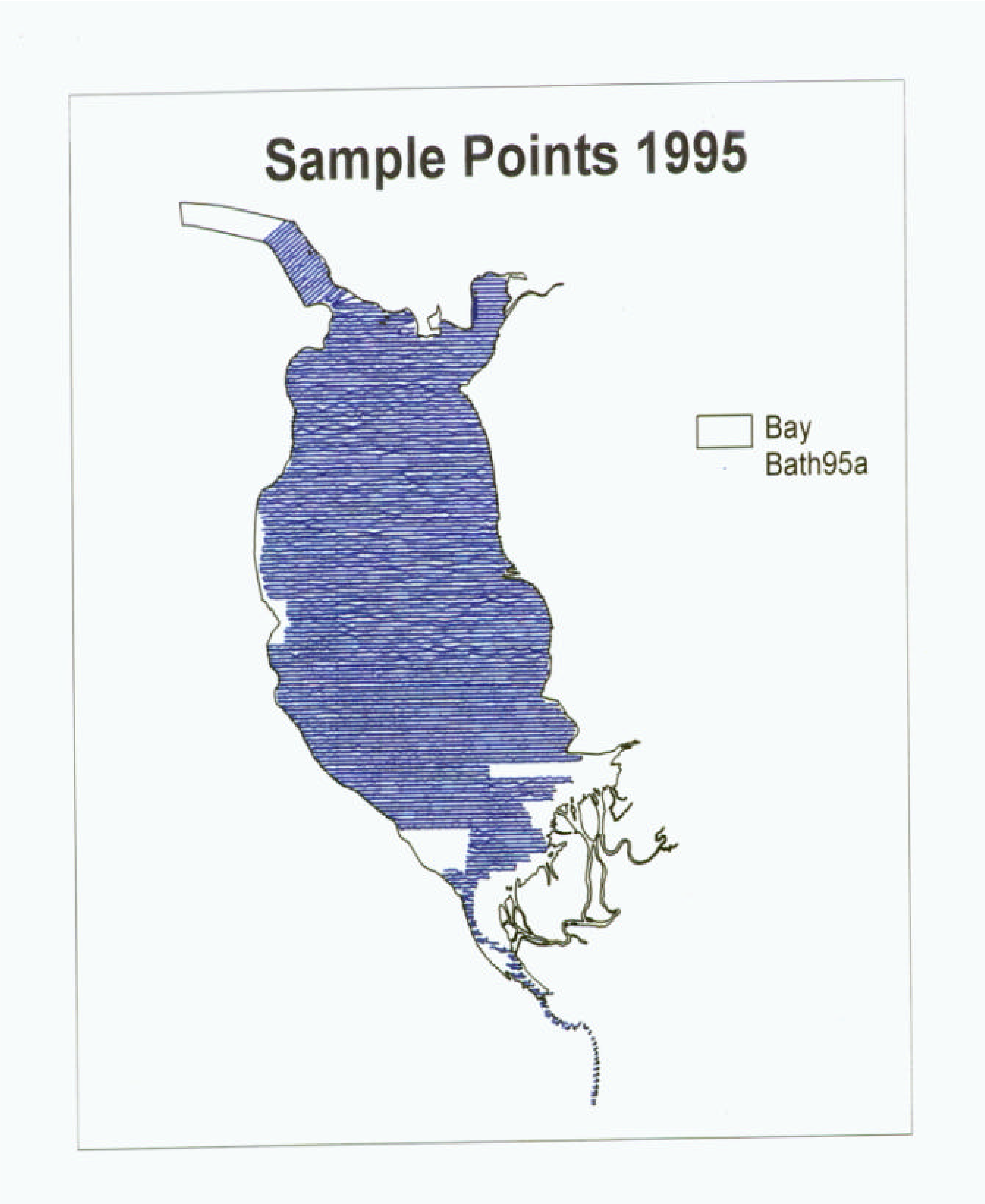

Figure 1c. Location of bathymetric data points derived from surveys conducted in 1995.

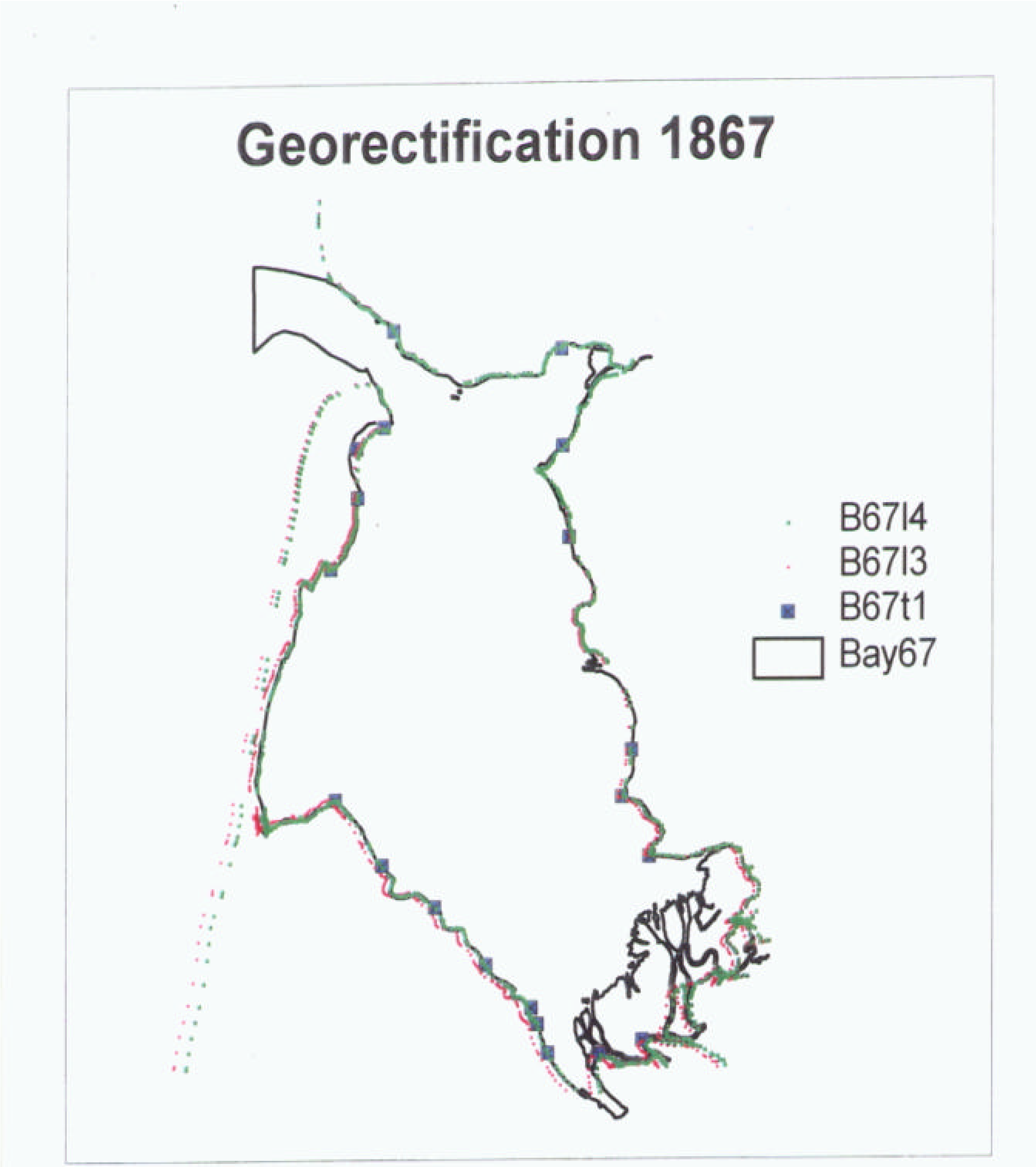

Figure 2. Map showing extent of correction of x-y positions of bathymetric data points collected in 1867. The map shows the location of the bay outline in the 1867 data base (dotted red line), the current bay outline (solid line) and the location of 20 points along the shoreline that were assumed to have remained stable during the intervening time period. The bay outline was transformed (rotated, skewed, and scaled), so as to achieve the greatest agreement possible between the 1867 bay outline and the current bay outline for these 20 points. The corrected bay outline is shown as a dotted green line. This same correction was applied to all data points in the 1867 survey.

1995 Bathymetric Data/Map

Bathymetric points for 1995 were collected by the U.S. Army Corps of Engineers in 1994 and 1995. The data were collected from 49,084 sample points in linear paths across the bay (Figure 1c). The transects were generally about 200 m apart with samples 30 m from one another. This represents a sampling intensity of 7.5 times the sampling frequency employed in 1957, and 13 times the frequency employed in 1867. These sampling differences have an important influence on the errors associated with preparation of the respective bathymetric maps.

3. Development of Bathymetric Surfaces

We developed bathymetric maps for each of the data sets in a consistent fashion. This allowed direct comparison between surveys to permit quantification of the changes that occurred in the depth of the bay during the intervening periods. The bathymetric coverages were developed by interpolating surfaces from the survey data points.

Many different interpolation techniques exist for generating surfaces from point measurements. We chose to use ordinary kriging because it is well suited to irregularly spaced data, is custom fit with a geostatistical model, and allows for calculation of variance associated with the interpolation. Kriging is one of the most common geostatistical methods for interpolating point data into three-dimensional surfaces. It is a least squares prediction method that includes a spline interpolation (Jernigan, 1986), and it assumes that the spatial variability in a surface is statistically homogeneous throughout the data. Kriging calculates a weighted moving average equation which estimates the true value of a regionalized variable and site specific location (Deutsch and Journel 1992, Cressie 1991).

In order to perform kriging, the spatial correlation structure of the data needs to be assessed. A variogram model provides the interpretation of the correlation structure of the data (Englund and Sparks 1988). The variogram is used to evaluate the spatial correlation of data points in the data base (Webster and Oliver 1990). This is determined by representing the correlation among sample points separated by specific distances (y(h)). The equation for y(h) is:

$$y(h) = \frac{1}{2n} \sum_{i-1}^{n} \{ x_i - (x_i + h)\}^2$$

The model was fitted interactively and graphical examination of the semivariogram assisted in determining a good model fit (Jernigan 1986). A Gaussian distribution was chosen to fit the model to the data. The model follows the form:

$$y(h) = C_O + C\left(1 - exp\left(\frac{h^2}{r^2}\right)\right)$$

where

h > 0
y(0) = 0
C is the scale for the structure of the variogram
h is the anisitropically scaled relative distance

The model parameters for the semivariograms are presented in Table 1.

The range (r) of the semivariogram for 1867 was 584 m, as compared with 271 m in 1957 and 481 m in 1995 (Table 1). This indicates that the interpolation utilized data within these ranges to develop the respective surfaces. The smaller range in the 1957 database is reflected in the larger variance for that data set. It suggests that the 1957 data had greater local heterogeneity which may have been due to a combination of errors and data collection methods.

The optimum grid size for constructing the bathymetric surfaces was determined based on examination of the sampling distribution for the three periods. The resolutions of the 1995, 1957, and 1867 data were significantly different but needed to be standardized for assessing change and comparing spatial patterns. A 30 m grid size was chosen for the analysis of each data set because:

1. This is comparable/compatible with USGS DEM data.
2. This resolution was adequate for comparing 1867, 1957, and 1995 grid data.
3. The output coverages have sufficient resolution for mapping spatial patterns within the bay.

Table 1. Semivariance model parameters used in the interpolations.			
Model Parameter*	1867	1957	1995
C_o	0.0	1.299	1.153
r	584.2	271.3	481.4
Sill	21.544	21.910	17.127

* C_o =nugget = displacement from zero to the y-intercept on the semivariogram plot
r =range of semivariance to the point where the rise in the semivariance levels off
Sill =the range of the y-axis of the semivariogram plot

The interpolated bathymetric maps are presented in Figures 3, 4, and 5. Variance maps that illustrate the variance or error associated with the interpolation are presented in Figure 6. The principal sources of error that are reflected in these variance maps are related to the density and spatial configuration of the sample points. The spatial configuration is critical in the kriging process and in all interpolation methods. The kriging weights (and correspondingly the variance estimates) are dependent on the variogram and not necessarily the measured values. This is why equidistant spacing is important in bathymetric data collection. Data were collected in both 1957 and 1995 along transects. Spacing of data points was much greater between transects than between points on a given transect. Such a sampling approach introduces unnecessarily large variance into the modeled bathymetric surface. The optimum sampling design would be either square grids (not rectangular) or equilateral triangles. Greater variance can also be associated with fewer data points within a given area, particularly where the available data points suggest an irregular surface.

Several sources of error can contribute to the overall accuracy of the mapped surface. Above we discussed quantification of the errors associated with the interpolation method (Figure 6). Many other sources of error are also included in the final bathymetric maps in addition to errors associated with the interpolation process. Unfortunately, we have little or no basis for quantifying

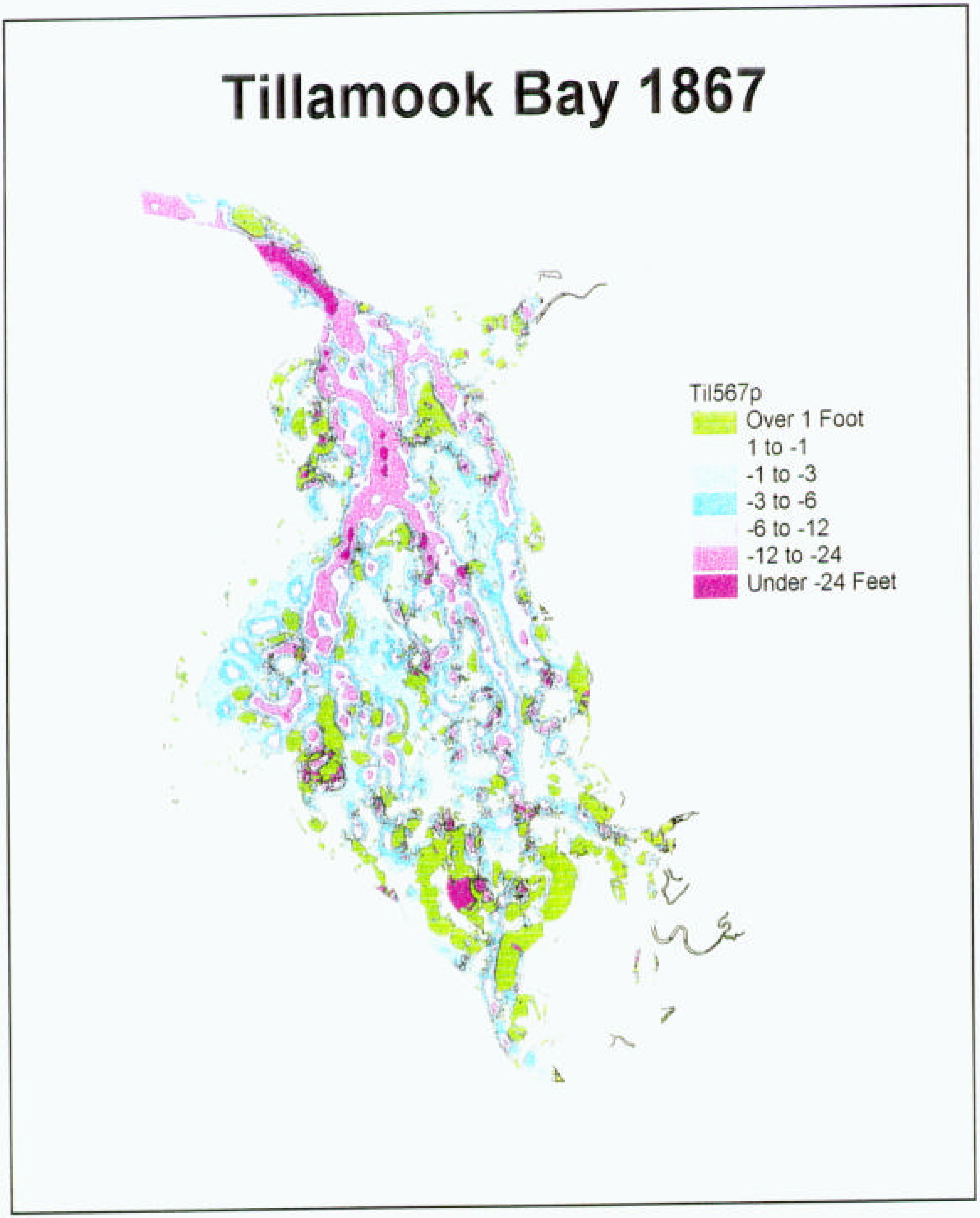

Figure 3. Bathymetric surface derived for 1867.

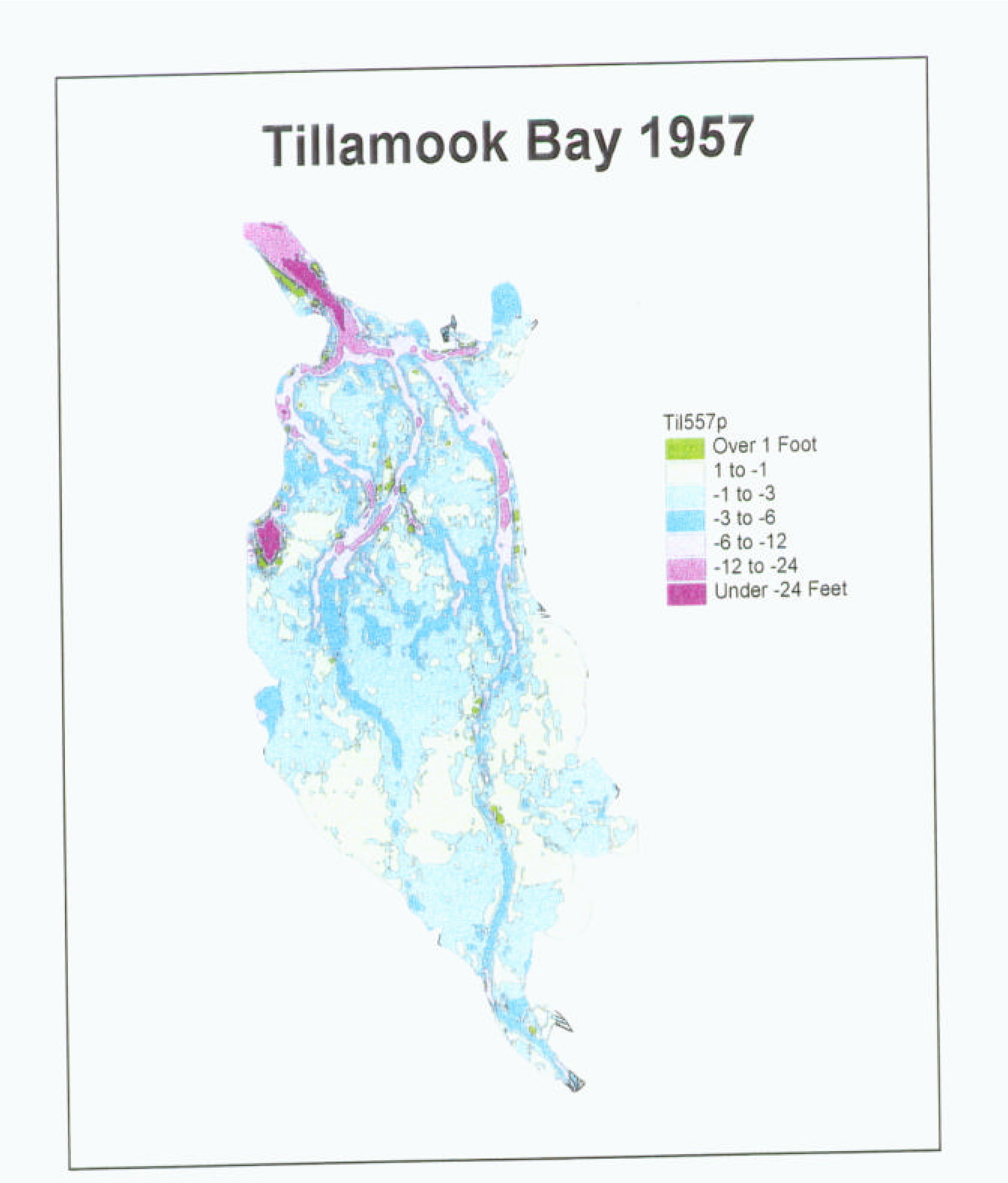

Figure 4. Bathymetric surface derived for 1957.

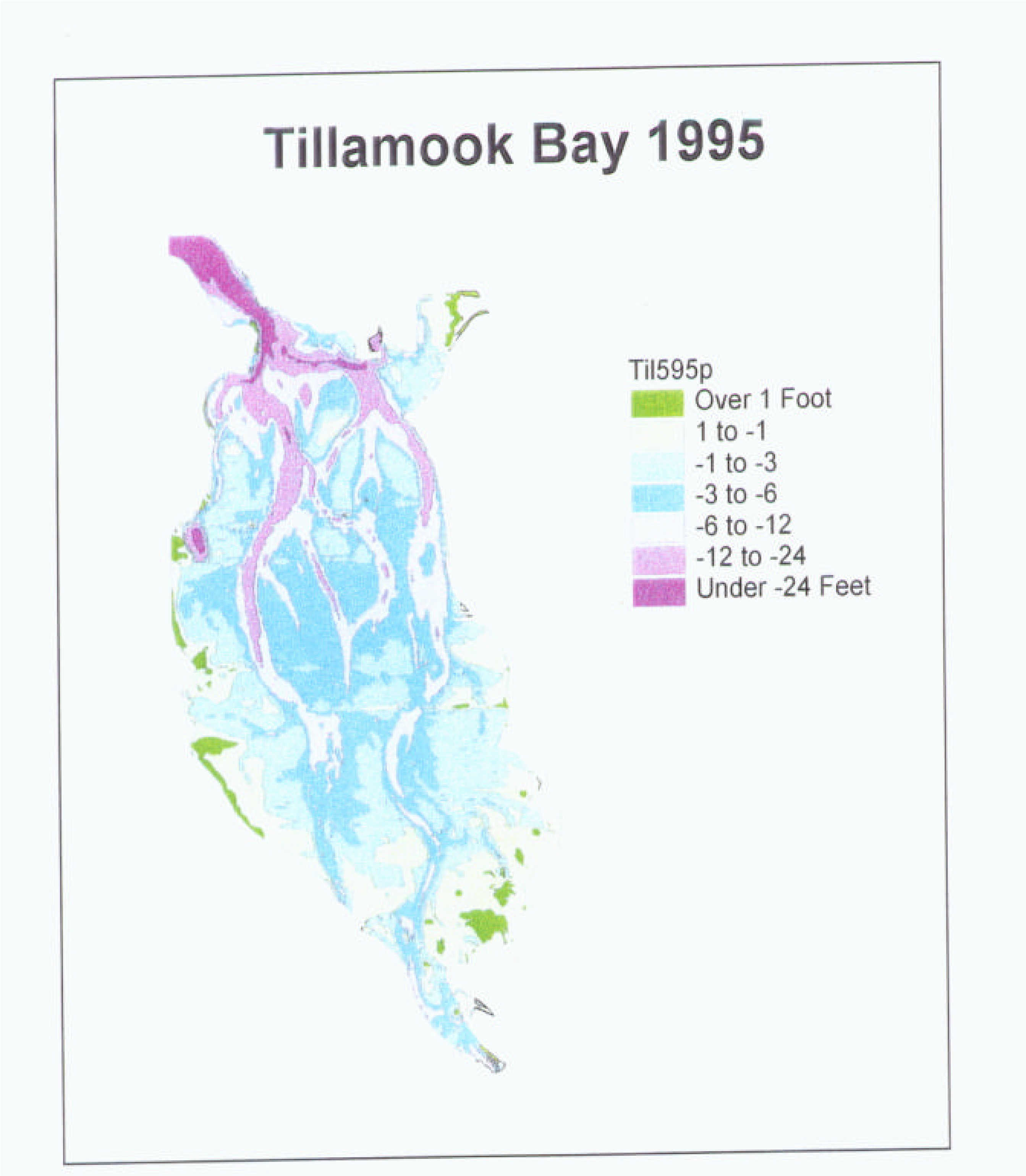

Figure 5. Bathymetric surface derived for 1995.

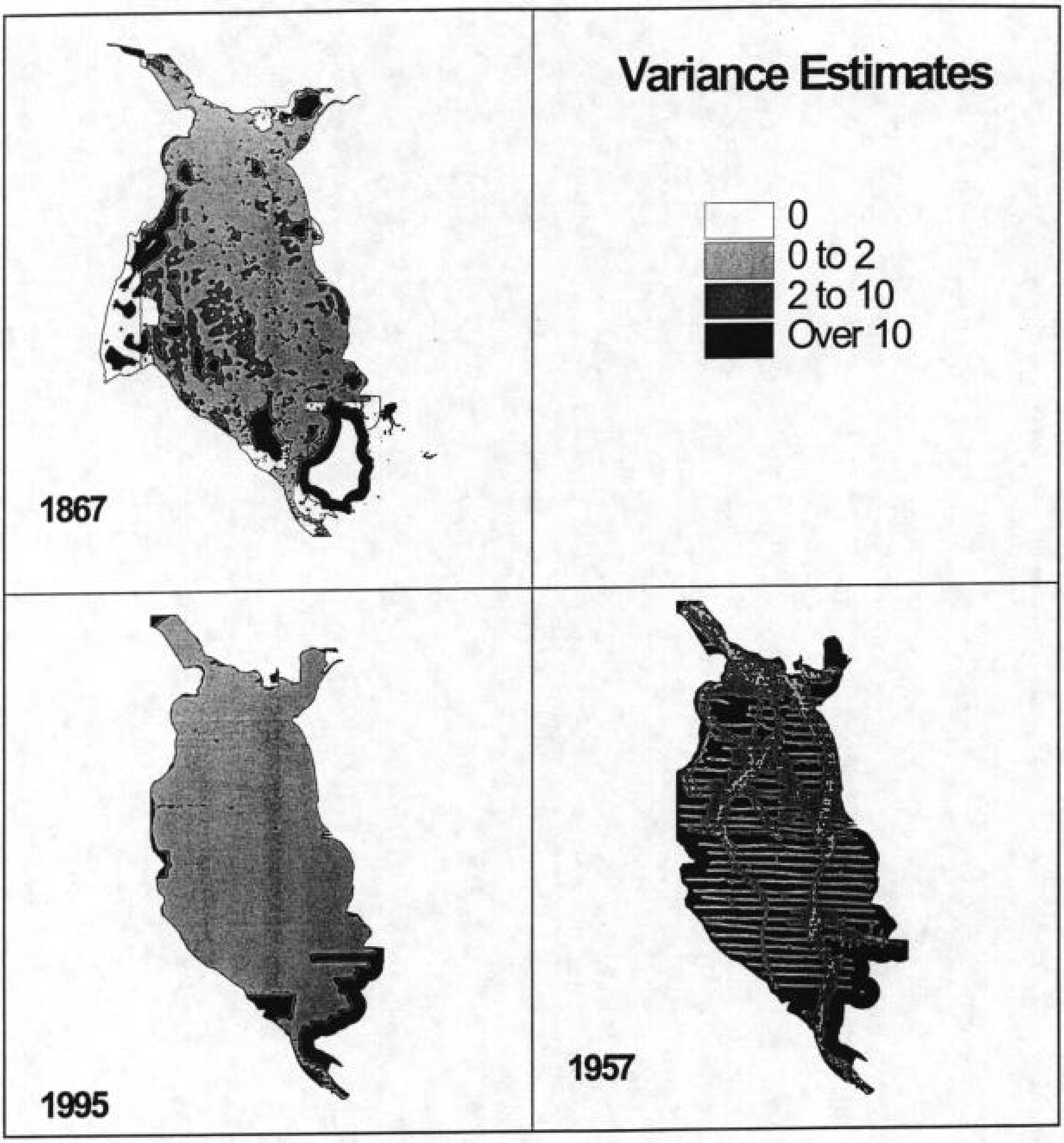

Figure 6. Variance in the interpolation methods for 1867 (a), 1957 (b), and 1995 (c). Note that this does not represent the total variance in the modeled (mapped) bathymetry. It only includes the portion of the variance that is associated with the kriging algorithm. Other important sources of variance are measurement errors, including the ability to standardize measurements to the tidal fluctuations. The latter were undoubtedly much larger in the earlier surveys.

those additional errors. These other potential sources of error in the bathymetric maps include errors associated with:

1. positional accuracy of the collected data,
2. depth measurements,
3. data entry and processing,
4. changing scale between and within data sets, and
5. the density and spatial configuration of the data points (Burroughs 1986).

3. Change Analyses

The major objective of this project was to attempt to quantify changes in the depth of Tillamook Bay during the intervening periods between the bathymetric sampling dates. As described previously, the variance associated with the interpolated surfaces for 1867 and 1957 were so large as to make that difficult or impossible for large areas of the bay. Measurement errors would add to that variance by an unknown amount, particularly for the historical surveys. In addition, there may exist a datum shift among the three bathymetric coverages. In other words, for each data set, the measured depths had to be standardized to some benchmark elevation. For example, a depth can be recorded at -3 ft., but we need to know the answer to the question, "Three feet below what?" We do not have information on how the historical data sets were referenced, but we suspect that the reference points were probably not the same. Komar (1992) suggested that data on global sea level and local elevation changes indicated that, between 1931 and 1988, sea level has risen relative to the Tillamook area at a rate of 1 to 2 mm/yr. Assuming this rate has held since the first bathymetric survey, the rise in sea level in Tillamook Bay between 1867 and 1995 would be about 13 to 26 cm (0.4 to 0.8 ft). The official vertical datum shift of mean sea level was 4 ft between 1867 and 1957 and 3 ft between 1957 and 1995. Both of these vertical shifts in sea level were shifted upwards (Bruce Follansby, TBNEP, pers. comm.).

In Figure 7, we present the estimated change in depth from 1867 to 1957, assuming that there has been no appreciable datum shift between these data bases. The analysis suggests that some

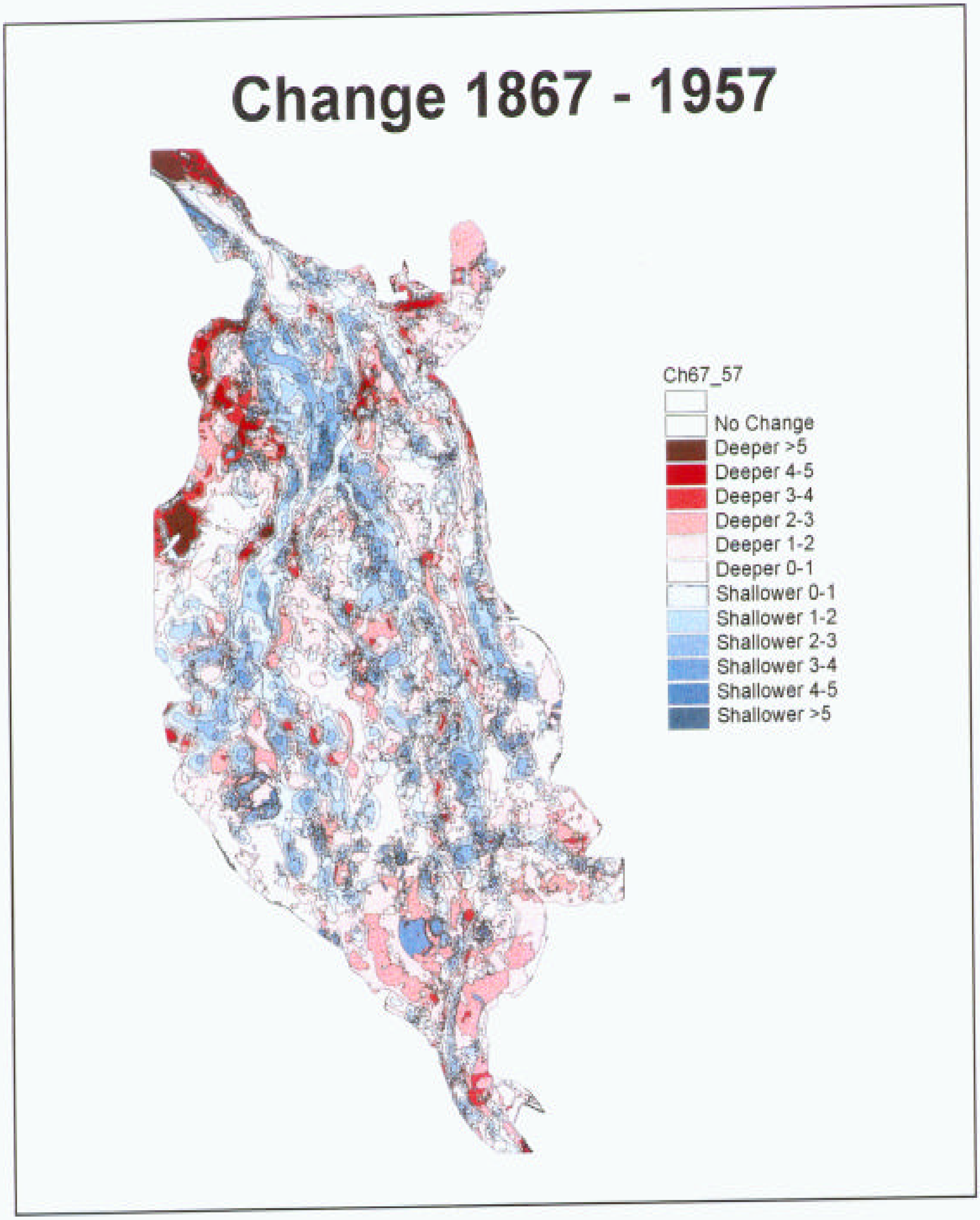

Figure 7. Inferred change in bathymetry from 1867 to 1957. No correction has been made for differences in benchmark elevation (datum shift) or sea level rise. Such corrections would change the inferences depicted here by an unknown amount.

portions of the bay became shallower and some became deeper, mostly by a small amount. A few areas were inferred to have become deeper by more than 4 ft., especially in the northwest corner of the bay. The inferred changes from 1957 to 1995 (Figure 8) were smaller, and many more areas were inferred to have become deeper than to have become shallower. Again, we assume no datum shift because we do not know what shift to apply to standardize these data sets. The overall inferred pattern of change (Figure 9) suggests that some parts of the bay became deeper since 1867, especially in the areas of the existing channels. Other parts were inferred to have become shallower. This interpretation might change if an appropriate datum shift could be applied to the 1867 bathymetry.

In Figure 10, the change analysis is presented again for the overall period 1867 to 1995. But in this case, the changes are color coded only for portions of the bay where the variance of the interpolations was less than 2 ft. For a large percentage of the bay (areas shaded in grey), the variance was considered too large to allow any meaningful estimate of change in water depth (even with ignoring the other sources of error and the likelihood that a datum shift had occurred by an unknown amount). For those areas with more acceptable kriging variance, some of the cumulative changes were towards a shallower bay and some towards a deeper bay.

The breach of Bayocean Spit between 1952 and 1956 resulted in the transport of large quantifies of marine sands into the Bay. Komar and Terich (1976) estimated the quantity of sand that entered the bay at the breach to be about 1.5 x $10^6 m^3$. Our map of inferred change in bathymetry from 1867 to 1957 (Figure 7) shows an extensive area of the bay in the vicinity of the breach that appears to have become shallower. This may be largely a result of the sedimentation associated with the breach.

4. Bathymetric Patterns

Differences in interpolation variance associated with development of the bathymetric surfaces and the likelihood of datum shifts between surveys, as discussed in the previous section make it difficult to precisely quantify differences in the inferred bathymetric patterns for the different survey

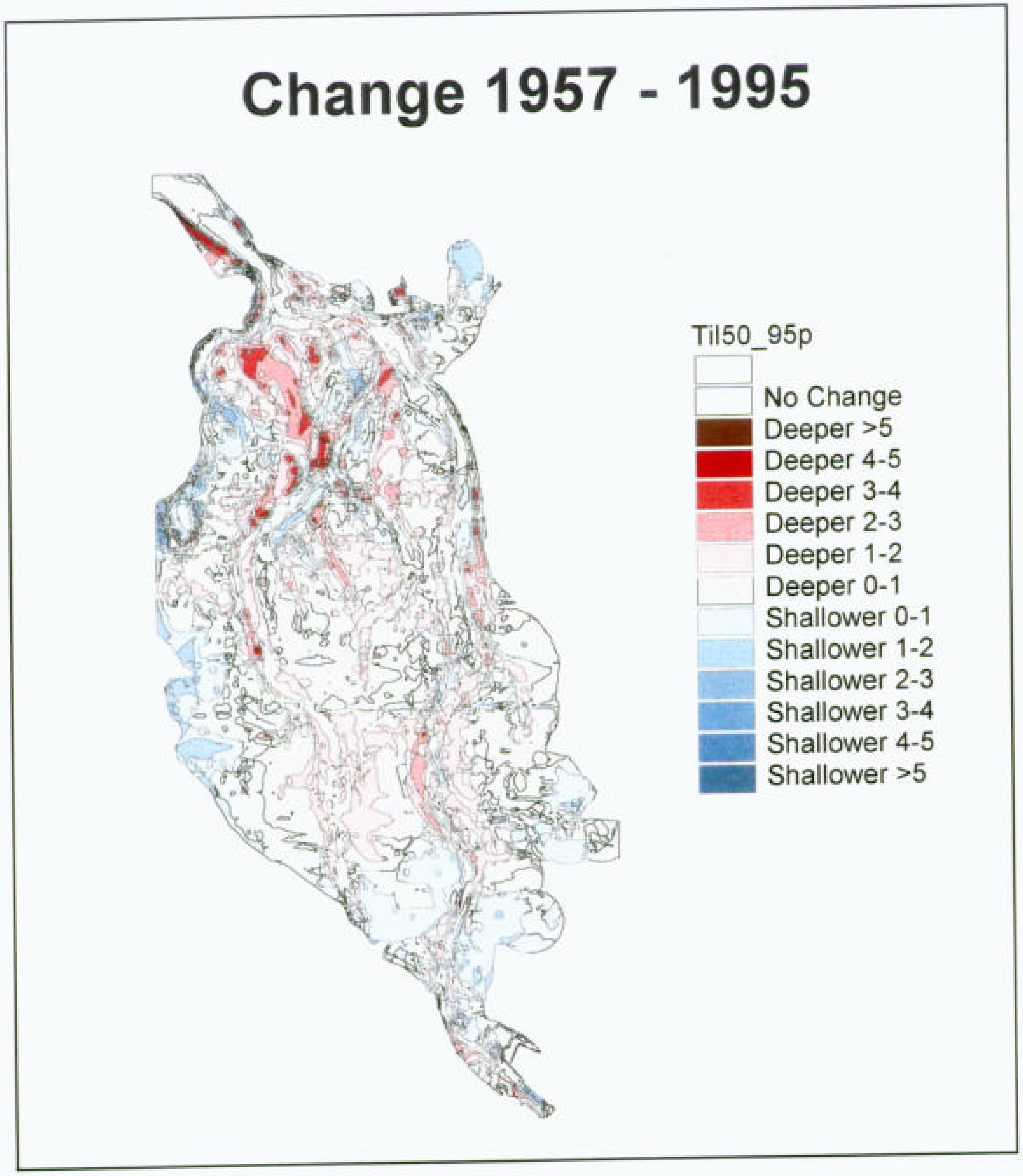

Figure 8. Inferred change in bathymetry from 1957 to 1995. No correction has been made for differences in benchmark elevation (datum shift) or sea level rise. Such corrections would change the inferences depicted here by an unknown amount.

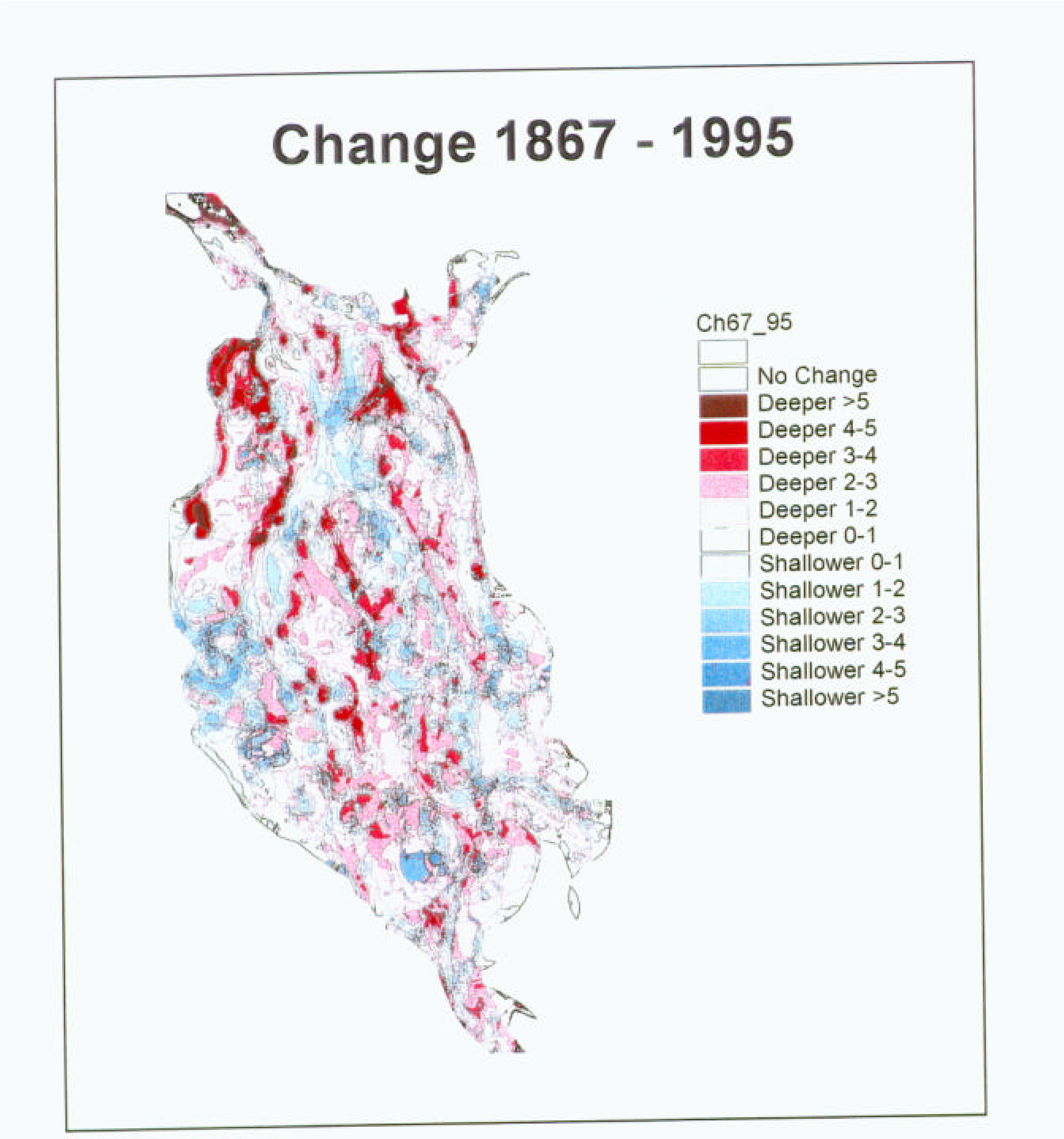

Figure 9. Inferred change in bathymetry from 1867 to 1995. No correction has been made for differences in benchmark elevation (datum shift) or sea level rise. Such corrections would change the inferences depicted here by an unknown amount.

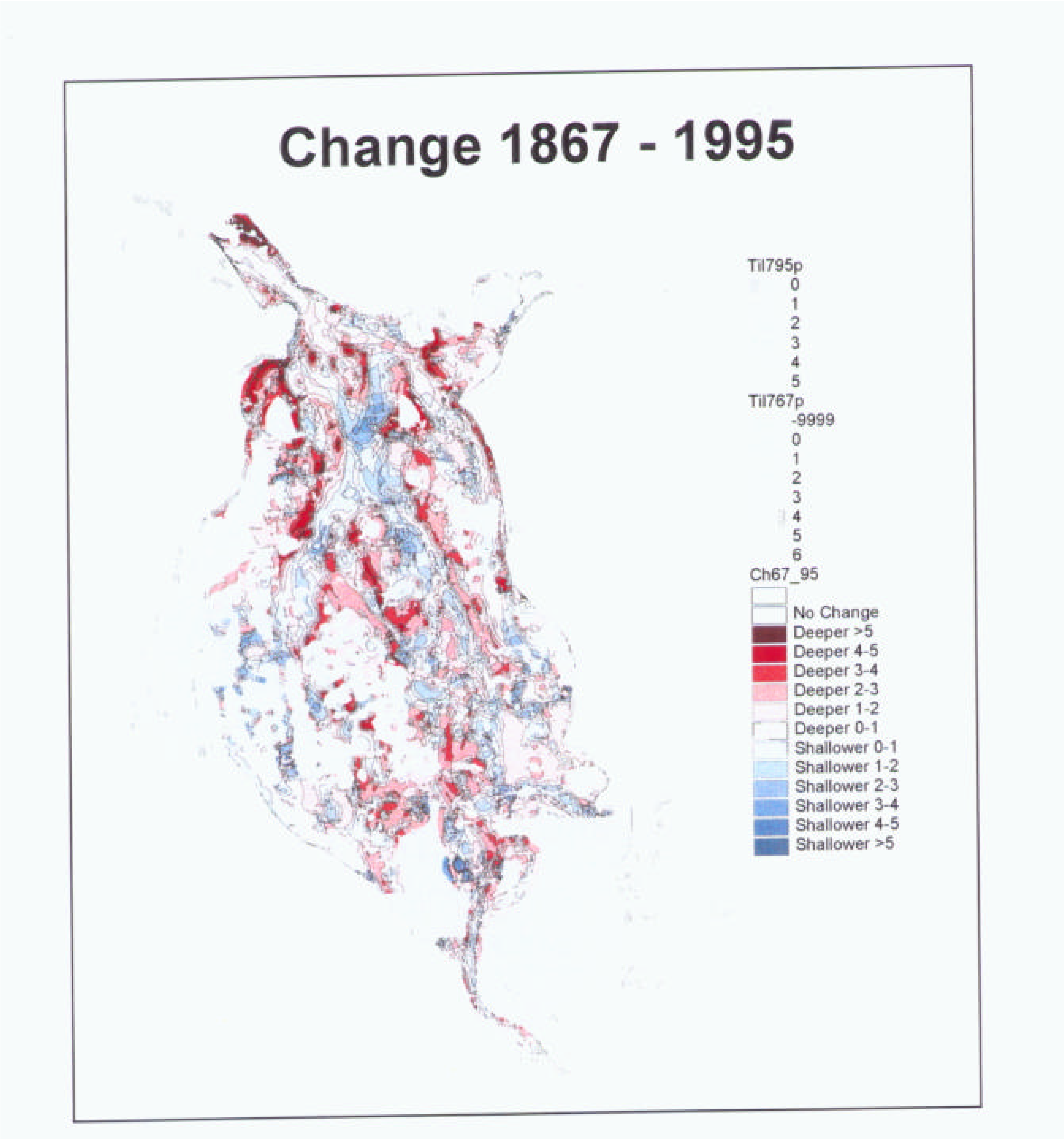

Figure 10. Cumulative change analysis for overall period 1867 to 1995, as shown in Figure 9, except that areas are represented in grey tone where the kriging variance was greater than 2 ft.

years. Additional errors associated with data collection may also impact the maps. It is a safe assumption that the relative errors associated with data collection are the smallest in 1995 and the largest in 1867. Errors associated with kriging were largest by a considerable margin for 1957. Thus, we are not able to quantify with confidence the changes in bathymetry that occurred. Nevertheless, the bathymetric surface developed for 1867 (Figure 3) suggests a very different pattern than was found for 1957 (Figure 4) and 1995 (Figure 5). The major difference observed was that the 1867 bathymetry reflects much greater overall complexity. The channels were deeper in many places and there were more deep (> 12 ft) holes scattered throughout the bay. This may have been due to the currents that would likely have been created by the presence of an abundance of large woody debris in the estuary at that time. Also, the 1867 bathymetry shows a scattering of shallower areas, particularly in the upper (southern) bay. Thus, the differences between deeper and shallower areas appears to have been more pronounced in 1867 compared to more recent surveys. This result must be interpreted with caution, however, because, many of the areas depicted as shallow (dark green) in 1867 (Figure 3) are also areas with poor sampling frequency (Figure 1) and therefore high variance (Figure 6).

The bathymetric maps for 1957 and 1995 are generally similar, and suggest a somewhat more homogeneous bay as compared with the 1867 map, and one that is more conspicuously marked by distinct channels. We know that channel dredging occurred between 1867 and 1957, and dikes were constructed during that period as well.

It is not clear, however, to what extent the different bathymetric pattern observed for 1867, especially the greater irregularity (bottom complexity), compared to 1957 and 1995 was due to real differences as opposed to merely increased errors associated with the construction of a bathymetric surface with an inadequate number of data points, as well as greater positional errors and measurement errors for 1867.

The variance associated with the 1995 bathymetric surface was good, in the range of 1 to 2 ft across most of the bay. This is partly a result of new data collection techniques that were not available in 1867 and 1957. The availability of linked global positioning systems (GPS) and

SONAR systems that collect and store x, y, and z coordinates instantaneously in an on-board computer data base now permit the collection of tens of thousands of data points in a fraction of the time required for the earlier surveys. The variance in this data set could have been reduced further by collecting data points in a more regular pattern (equidistant squares or triangles) rather than along transects.

The variance associated with the 1957 bathymetric surface illustrates the unfortunate nature of this survey. The spacing of data points along the horizontal survey transects was much less than the spacing between transects. Thus, the variance is low in strips across the bay that lie about each of the transects (Figure 6b). The variance between transects is high (> 10 ft).

5. Summary and Conclusions

We constructed bathymetric maps for Tillamook Bay for the periods 1867, 1957, and 1995, using a kriging interpolation approach. This allowed quantification of the variance associated with the interpolation process. We also noted several additional sources of error which we were not able to quantify. We judged that the variance in the interpolation approach, combined with additional errors associated with the water depth measurements and inadequate documentation of the benchmarks to which the measurements were standardized, were so large as to prevent us from quantifying the actual changes in the depth of the Bay that occurred during the intervening time periods. The results were consistent, however, with an interpretation of greater depth complexity and less channelization on average in 1867. We noted problems in the way the data were collected in 1957 and 1995 which introduced unnecessarily large variance into the mapped bathymetric surfaces.

References

Avolio, G.W. 1973. Granulometric analysis of recent sediments of Tillamook Bay, Oregon. M.S. thesis, Department of Earth Sciences, Portland State University, Portland, OR. 67 pp.

Chesser, S. 1975. The history of dike and jetty construction and dredging in Tillamook Bay. p. 6 in Miller and Garono.

Cressie, N. 1991. Statistics for Spatial Data. John Wiley & Sons, Inc., New York.

Deutsch, C.V. and A.G. Journel. 1992. GSLIB. Geostatistical Software Library and User?s Guide. Oxford Univ. Press, New York.

Englund, E. and A. Sparks. 1988. GEO-EAS (Geostatistical Environmental Assessment Software) User?s Guide. EPA/600/4-88/033. U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Las Vegas, NV.

Glenn, J.L. 1978. Sediment sources and Holocene sedimentation in Tillamook Bay, Oregon: Data and preliminary interpretations. U.S. Geological Survey, Open File Report 78-680. 15 pp.

Jernigan, R.W. 1986. A Primer on Kriging. U.S. Environmental Protection Agency Office of Policy, Planning and Evaluation, Washington, DC.

Komar, P.D. 1997. Sediment accumulation in Tillamook Bay, Oregon, a large drowned-river estuary. College of Oceanic & Atmospheric Sciences, Oregon State University, Corvallis.

Komar, P.D. and T.A. Terich. 1976. Changes due to jetties at Tillamook Bay, Oregon. Proceedings, 15th Conference on Coastal Engineering. Amer. Soc. Civil Engrs. pp. 1791-1811.

Percy, K.L., D.A. Bella, C. Sutterlin, and P.C. Klingeman. 1974. Descriptions and information sources for Oregon estuaries. Sea Grant College Program, Oregon State University, Corvallis.

Webster, R. and M.A. Oliver. 1990. Statistical Methods in Soil and Land Resource Survey. Oxford Univ. Press, New York.