CONF-9503121--3

Ninth Annual
Symposium
on Geographic
Information
Systems

GIS
95

Vancouver
British Columbia
Canada

Interpolation of Bottom Bathymetry and Potential Erosion in a Large Tennessee Reservoir System using GRASS

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A regularized spline with tension was used to interpolate a bathymetric bottom surface for the Watts Bar reservoir just south of Oak Ridge, TN, USA (Fig. 1) as part of an effort to predict the spatial distribution of radionuclide contaminants. Cesium 137 was released as a by-product of the production of fissionable materials during the mid-1950s. Cesium is strongly adsorbed onto clay and silt particles in the water column, and tends to settle to the bottom. An understanding of the shape and contours of the bottom is important for understanding and prediction of the location and extent of contaminated sediments. The results of our investigations are available on the World Wide Web (WWW) at URL:

http://www.esd.ornl.gov/programs/CRERP/INDEX.HTM

The Waterways Experiment Station (WES) of the U.S. Army Corps of Engineers conducted a hydro-acoustic study of the Clinch River arm of Watts Bar Reservoir to determine the distribution, thickness, and type of bottom sediments that had accumulated since completion of Watts Bar Dam in 1942. WES has developed, through the Dredging Research Program (DRP), a rapid geophysical technique to determine material characteristics of bottom and subbottom sediments (Caulfield and Yim 1983). Acoustic impedance values determined from seismic reflection data are directly related to the density and material type of the subbottom sediments (Hamilton 1970, Hamilton and Bachman 1982). Results indicate good correlation between the values determined with this technique and in situ information collected at several sites.

The objective was to quantify with depth the density and type of bottom and subbottom sediments up to depths of 15 ft below the bottom surface along the Clinch River and Poplar Creek, TN (Fig. 1). The results supplement sediment core samples previously taken in each study area by providing continuous profile line coverage along the entire length of the study area.

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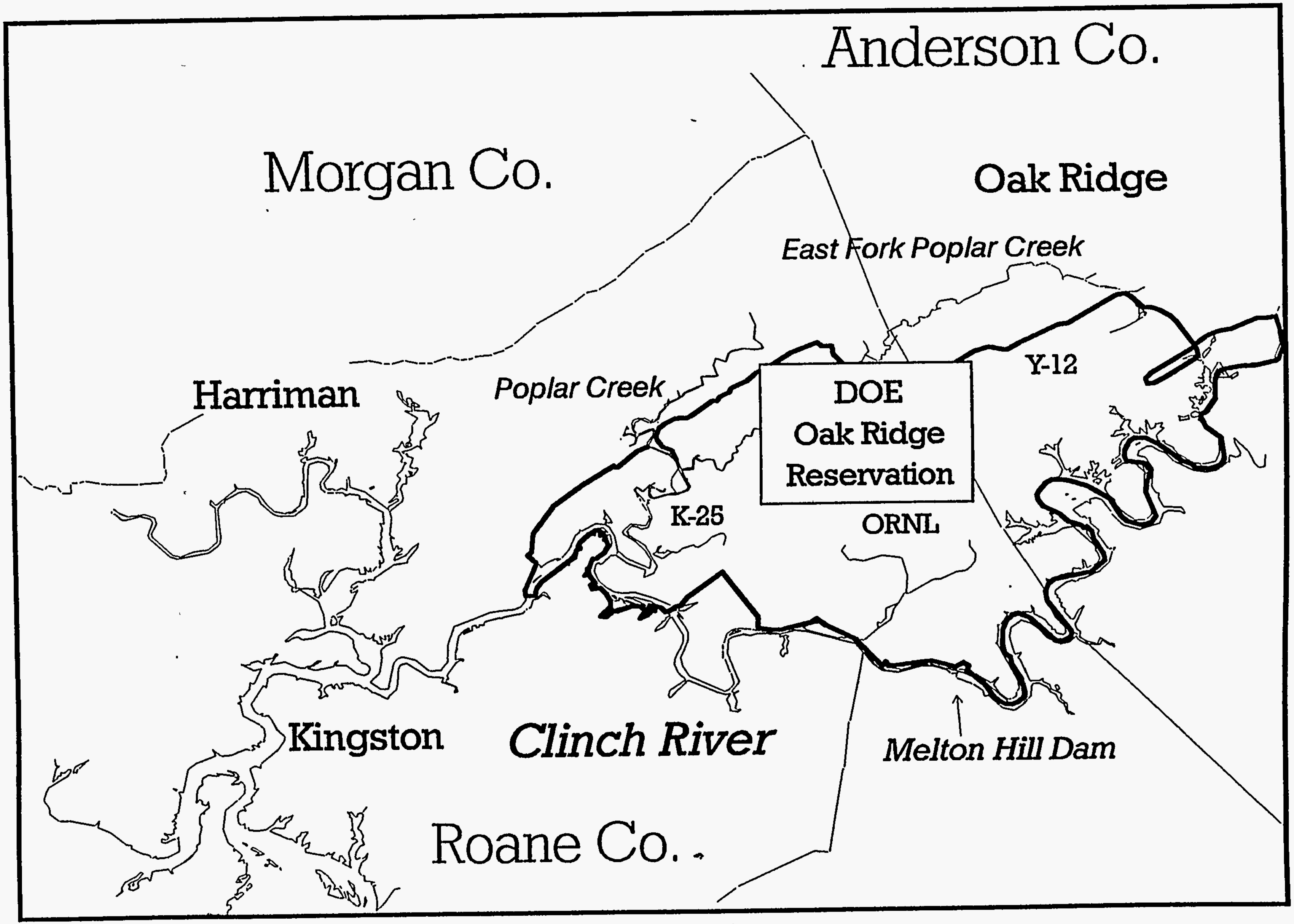

Figure 1: *Clinch River study area*

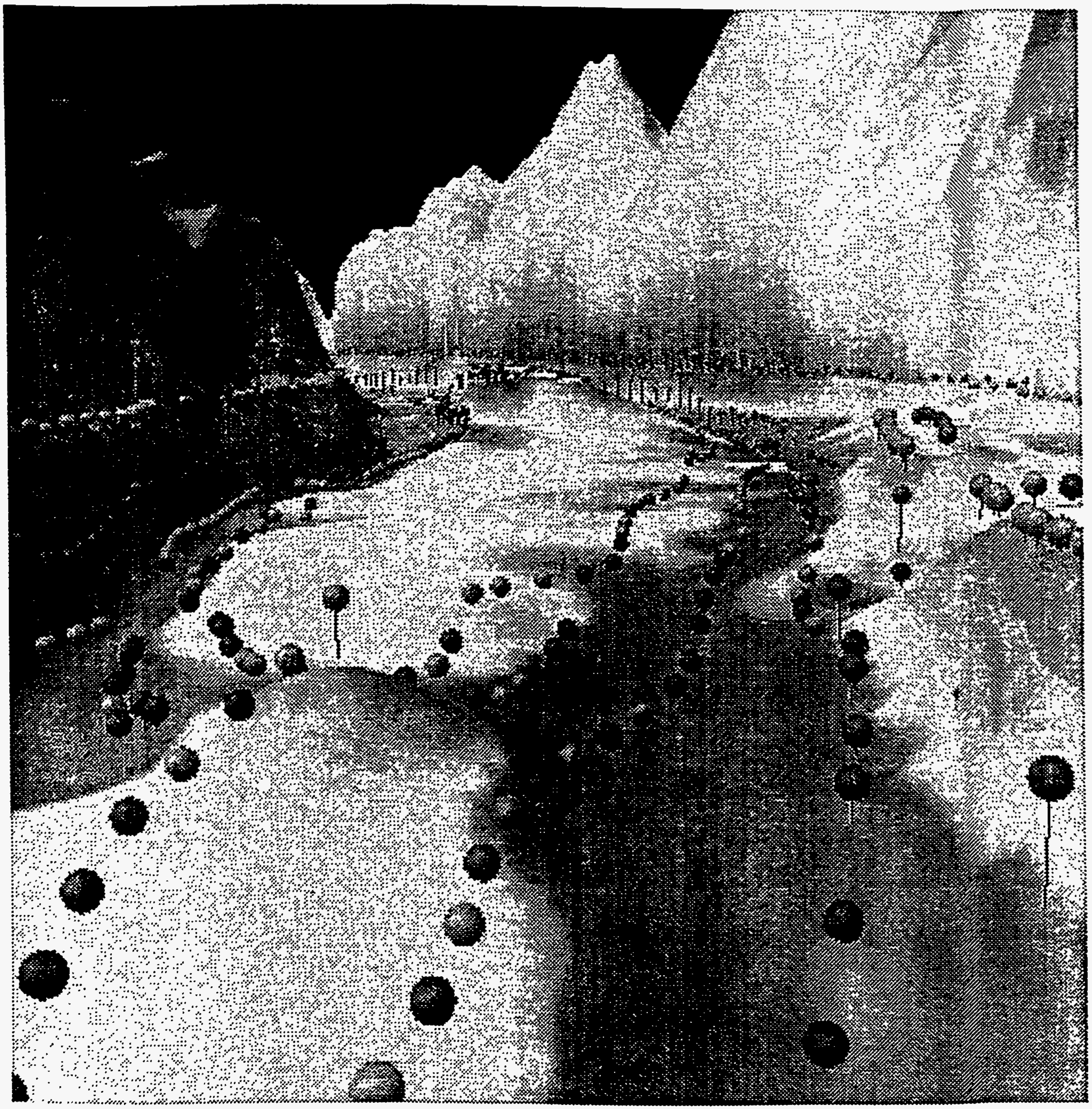

Figure 2: *Error pins placed in the drained Clinch River bottom indicate the difference between the splined surface and the actual depths*

trends in residual errors (Fig. 2). At each of the data locations, the height of the interpolated surface was subtracted from the true depth. A green pin indicates that this delta was positive, and a red pin indicates that this difference was negative. The absolute value of this difference was added to the height of the surface, and the pin heads were positioned at this height.

Thus, the head of the virtual push-pin is green if the interpolated bottom surface should have been higher at the pin location, and red if the surface should have been lower at this spot. The surface should have passed through the center of the heads of the green pins; it should have passed through a spot as far below the surface of the red pins as the red pins are tall.

Short alternating red and green pins indicate a nearly perfect fit of the interpolated surface with the actual known depths. Alternating red and green pins of greater height indicate that the spline has "smoothed out" a rough bottom (or a series of noisy depth measurements). A perfect match (to the nearest hundreth of a foot) between spline depth and actual depth data is indicated by white pins whose heads rest on the bottom.

A tension setting of 130 with a smoothing of 0.5 foot was found to produce the best surface with the smallest and least spatially-correlated residual errors. An MPEG-format animated visualization flying over the final version of the bathymetric surface, with associated error pins, was produced, and can be seen on the WWW at the URL:

An array of geophysical instruments were utilized, including:

- a 3.5 kHz high resolution 'pinger' system,
- a 1.0 to 10.0 kHz high definition, broad spectrum acoustic profiling 'chirp' system, and
- a dual frequency side-scan sonar system.

This equipment produced the necessary seismic energy to obtain reflection signatures from the bottom and subbottom lacustrine sediments. Primary channels of acoustic data were acquired with a digital data acquisition system. Data were collected in near real-time during the survey, allowing continual data quality control. Acquisition and interpretation of traditional 'shades-of-gray' analog reflection records were performed concurrently with the digital acoustic impedance techniques.

Position information for the survey was provided by continuous, real-time differentially-corrected Global Positioning System (GPS) receivers. A GPS fix was appended to each sonar reading to provide lateral positioning in the river with a high degree of accuracy.

The WES survey resulted in depth soundings at a total of 6,589 locations. These remotely-sensed data were combined with information from a number of additional sources. The shoreline of the river was obtained from the USGS DLG hydrography files. Prominent contour lines, as well as the outline of the deep center channel, were digitized from Tennessee Valley Authority (TVA) navigation charts. Ancillary in-house GPS-located sounding data were available for Poplar Creek. TVA had permanent siltrange transects across the river, along which depths had been measured, in order to estimate the amount of siltation that had occurred in the reservoir. Similarly, a number of depth transects were available near the mouth of Poplar Creek, where a submerged pipeline was to be installed. Finally, depths were recorded at locations where either sediment cores or sediment grab samples had been collected. After these data sources were combined, depths were available for a total of 93,441 locations on the river.

GRASS (Geographic Resources Analysis Support System) (Anon. 1991) was used, in conjunction with custom shell script programming, to prepare the sites for the interpolation of a complete bottom surface. A thin-plate spline function was chosen as an interpolation technique. The spline interpolator is generally regarded as superior to less sophisticated techniques like inverse distance weighting, and, unlike kriging, allows for interpolation of non-stationary surfaces.

The regularized smoothing spline with tension is a radial basis function method for interpolation from scattered data. This interpolation technique is flexible, since it allows the choice of a tension parameter which controls the properties of the interpolation function, and a smoothing parameter, which filters out noise in the data. The function has regular derivatives of arbitrary order, and can be used for interpolation along multiple dimensions. This method has been developed by Lubos Mitas at NCSA, and was been implemented in GRASS by Helena Mitasova and Irina Kosinovsky (see Mitasova and Mitas 1993, Mitasova and Hofierka 1993).

Conceptually, the spline acts as a sheet or plate which bends up or down to pass close to known data (Talmi and Gilat 1977). As the tension parameter is increased, the characteristics of the surface change from a stiff plate, which bends slowly, to more like a thin rubber membrane, which easily flexes to meet data points. The smoothing parameter controls how much the surface is allowed to "miss" the known data points; a smoothing factor of 0 forces the splined surface to pass exactly through the data. Smoothing can be used to discourage the generation of overshoots in the interpolated surface by allowing some "miss", which is associated with the uncertainty with which the data themselves have been measured (Mitasova 1993a, 1993b).

A number of additional parameters control how the spline algorithm segments the plane into neighborhoods, each of which contains a user-specified number of data points. Each individual neighborhood is considered separately by the spline. To ensure a smooth connection with no visible "seams" between neighborhoods, the algorithm considers a user-specifiable number of data points outside the current neighborhood. Adjustment of these segmentation parameters allows the interpolation of a seamless surface for nearly any spatial dispersion of data points.

The spline algorithm is rather computer-intensive. To minimize computational resources necessary to produce a splined surface, the algorithm weeds out or thins data points where their spatial density exceeds a user-specified density. In order to simplify the problem, we set the spline interpolator to consider only data points that were more than 10 meters from other data points. Maps were created with a spatial resolution of 5m.

We had greater confidence in the "primary" depth data from the WES acoustic survey and the pipeline transect survey than the "secondary" depth data from sources like contour lines, channel markings, etc. However, there is no provision for weighting various input data differently to reflect differences in confidence or data quality. We created spatial buffers 20m around each of the primary data locations, and used this buffer layer to "mask" the secondary data. Thus, secondary data were included in the spline only if they fell more than 20m from primary data locations. This technique ensured that primary data were used where they were available, yet used the data from secondary sources to fill in "gaps" in the spatial dispersion of primary data.

To choose appropriate values of tension and smoothing, a small area was chosen and a smooth surface was repeatedly interpolated through the depth data points in this area through a wide range of tension settings, ranging from 5 to 300. When the tension setting is too low, the interpolated bottom surface does not flex fast enough to come up to the shoreline on both sides of the river; when tension is too high, the surface flexes so easily that it greatly overshoots the data, and deep pits are formed in the bottom.

Three-dimensional visualization (SG3d, Brown and Gerdes 1992) was used to check the appearance of the resultant interpolated surface, and to look for spatial http://www.esd.ornl.gov/projects/CRERP/SEDIMENT/PINHEAD.HTM

In this MPEG animation, the interpolated elevation surface is draped with colors representing the output from a spatial filter which estimates the potential erosion or deposition which could occur at each spot on the bottom. An adaptive spatial filter was created to indicate whether each point in the bathymetry map represented a local high spot, a local depression, or part of an abyssmal plain. This local bathymetric environment should reflect the no-flow erosion or deposition potential at that site. The GRASS raster map algebra tool, r.mapcalc, was used to program a 105 m diameter spatial "erosion" filter which has 4 "spokes" in each of the sub-cardinal compass directions. The Erosion filter uses an inverse distance squared weighting, so that cells closer to the center have more effect than those toward the edges of the filter. The filter returns the signed log of the difference between depth at the center cell and the weighted average depth over all "spokes".

Red and yellow colors represent locations which are higher than the local surroundings, and are therefore potential erosion sites. Green and blue colors are found at points that are lower than their immediate surroundings; such areas are potential deposition sites. Flat areas are colored white and are neither potentially erosional or depositional.

The Potential Erosion Filter

The Adaptive Spatial Erosion Filter, or "spoke" filter, is a geometric pattern that is passed over the bathymetry surface such that the center cell, or "focus" of the wagon wheel passes sequentially over each cell in the bathymetry map. At each position, the depth in each cell of each of the spokes is multiplied by a weighting factor, and a weighted average depth is calculated. This weighted average depth is compared to the depth under the focus cell, and the signed log of the difference is written to a second map.

We have experimented with 3 weighting functions, all of which result in cells that are farther from the focus cell having less weight than cells which are closer to the filter focus. We have produced a filter where the weighting decreases linearly with increasing distance from the focus, one where the weights decrease as reciprocal distance, and one where weights decrease as inverse distance squared. All of the simulations shown here use the results from the reciprocal distance erosion filter.

If the depth at the center focus cell is higher than the weighted average of the surrounding local environment, that cell could potentially erode. On the other hand, if the center focus cell is at a local low spot relative to its surroundings, the filter indicates that potential deposition could occur. The behavior of the filter is log-transformed, since very deep "holes" or very tall "peaks" would not be that much more likely to erode or deposit than shallower ones. The Erosion filter can predict only potential erosion and deposition, since, for example, the existence of local low spots does not guarantee the availabliity of sediment to deposit there.

The radius of the filter is adjustable. The radius chosen, however, has a rather minor effect on the filter results, since the weights cause cells farther from the focus to have diminishing effects anyway. Experimentation has shown that realistic-looking results are produced with a radius of 105 meters, and this is the radius that has been used for the simulations on the WWW. Ultimately, we plan to statistically resolve among the 3 weighting functions and converge on the best radius for the potential erosion/deposition filter by comparing the contribution of the filter results obtained using each technique to the explanatory power of an ANOVA for predicting Cesium 137 contaminant concentrations found in sediment cores and grab samples.

The development of an interpolated bathymetric surface allowed for the production of a hypsograph, which specifies the relationship between particular fill levels in the reservoir, the area covered by water at that fill level, and the volume of water contained in the reservoir at that fill level. A customized shell script was used to perform the cut-and-fill calculations to produce areas and volumes. A curve showing the additional area of bottom sediments exposed by lowering the water level was also generated by subtraction. Area of sediment exposed is useful for calculation of human health risks associated with increased exposure to contaminants in the bottom sediments. Separate hypsograph curves were produced for Clinch River and Poplar Creek by masking the areas of interest and repeating the cut-and-fill shell script. The Clinch River hypsograph can be seen on the WWW at URL:

http://www.esd.ornl.gov/programs/CRERP/SEDIMENT/HYPSO.HTM

The analysis of the acoustic survey of bottom sediments in the Clinch River and Poplar Creek did not and will not stop with the production of the bathymetric surface. At the National Laboratory, we are using the remotely-sensed surface densities to interpolate a continuous sediment density map of the bottom surface, and now we are beginning to analyze the acoustic impedance data for sub-bottom sediment densities (see Levine et al. elsewhere in this volume). Three-dimensional visualization has proved to be very useful for understanding interpolation results, and for minimizing errors. Such multidimensional cartography may well be the future of GIS (Mitasova et al. 1994). We believe that visualization will be critical for interpretation of sub-bottom information, the delineation of potentially contaminated locations, and the evaluation of remediation strategies.

References

Anon. 1991. Geographic Resources Analysis Support System Reference Manual, Version 4.1 U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, IL.
(also see URL http://www.cecer. army.mil/grass/GRASS.main.html)

Brown, W., and Gerdes, D.P., 1992. SG3d - supporting information. URL http://www.cecer.army.mil/grass/viz/sg3d.html

Caulfield, D.D., and Yim, Y.C. 1983. Prediction of shallow subbottom sediment acoustic impedance while estimating absorption and other losses. J. Canadian Soc. Exploration Geophysicists 19(1):44-50.

Hamilton, E. L., 1970. Sound velocity and related properties of marine sediments. North Pacific J. Geophys. Res. 75(23):4423-4446.

Hamilton, E. L., and Bachman, R.T. 1982. Sound velocity and related properties of marine sediments. J. Acoustics Soc. Am. 72(6):1891-1904.

Hutchinson, M. K. and Gessler, P. E., 1993. Splines: More than just a smooth interpolator, Geoderma.

Mitasova, H., Brown, W. M., and J. Hofierka, 1994. Multidimensional Dynamic cartography. Kartograficke listy 2:1-7.

Mitasova, H. and Mitas, L., 1993. Interpolation by regularized spline with tension: I. Theory and implementation, Mathematical Geology No.25 p.641-656.

Mitasova, H. and Hofierka, L., 1993. Interpolation by regularized spline with tension: II. Application to terrain modeling and surface geometry analysis, Mathematical Geology No.25 p.657.

Mitasova, H., 1993a. Surfaces and modeling, GRASSclippings, v.6, No.3 (winter), pp 16-18

Mitasova, H., 1993b. Surfaces and modeling, GRASSclippings, v.6, No.4 (spring).

Talmi, A. and Gilat, G., 1977. Method for smooth approximation of data, Journal of Computational Physics, 23, pp 93-123.

Acknowledgment

Research sponsored by Office of Environmental Restoration and Waste Management, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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