Bibliotheek TU Delft Uitsluitend voor eigen gebruik / for own use only

Prometheusplein 1
Postbus 98
2600 MG DELFT
Telefoon: 015 - 2784636
Fax: 015 - 2785673
Email: Klanten-Service@Library.TUDelft.NL

Datum: 07-apr-03

Bonnummer: 648364

Aan: VLAAMS INSTITUUT VOOR DE ZEE
VISMIJN
PAKHUIZEN 45-52
B 8400 OOSTENDE
BELGIE

Tav:

Aantal kopieën: 10

Uw referentie(s): 1521549 1521549

Artikelomschrijving bij aanvraagnummer: 648364

Artikel: Overview of GIS Applications in Estuarine Monitoring and A
Auteur: John F Paul et al.
Tijdschrift: MARINE GEODESY
Jaar: 2003 **Vol.** 26 **Aflevering:** 1/2
Pagina(s): 63-72 **Plaatsnr.:** GEPR

Met ingang van 1 april 2003 zullen de prijzen voor fotokopie levering buitenland stijgen met € 0,05 per pagina

From April 1 2003, prices for photocopy delivery abroad will increase by € 0.05 per page

Marine Geodesy, 26:63–72, 2003
Copyright © 2003 Taylor & Francis
0149-0419/03 $12.00 + .00
DOI: 10.1080/01490410390181207

Overview of GIS Applications in Estuarine Monitoring and Assessment Research

JOHN F. PAUL

Atlantic Ecology Division
U.S. Environmental Protection Agency
Narragansett, Rhode Island, USA

JANE L. COPELAND
MICHAEL CHARPENTIER

Computer Sciences Corporation
Narragansett, Rhode Island, USA

PETER V. AUGUST
JEFFREY W. HOLLISTER

Department of Natural Resources Science
University of Rhode Island
Kingston, Rhode Island, USA

Geographic information systems (GIS) tools are now considered integral in estuarine monitoring and assessment research. A synopsis is presented of our estuarine applications of GIS in the Northeast region of the U.S. The applications discussed cover sample site selection, support for field sampling activities, quality assurance of data, spatial display of geographic referenced information, quantitative spatial analysis of data, and communication of results.

Keywords estuaries, monitoring, GIS, spatial displays, spatial analysis

Geographic information systems (GIS) are now considered common-use technical tools in the environmental sciences. This was not so about a decade ago. With the proliferation of computing power at the desktop and the wide-spread availability of sophisticated software, GIS tools have been increasingly used over this past decade (USEPA 1995). These tools have been particularly useful for estuarine monitoring and assessment research at the U.S.

Received 4 March 2002; accepted 20 June 2002.

We thank Dianne Nacci, Mona Haebler, Anne Kuhn, Matt Nicholson, and two anonymous reviewers for their critical comments. JLC and MC supported through contract 68-W-01-032, Larry Rossner, Task Order Delivery Officer. JWH supported through Cooperative Agreement CT825802, Brian D. Melzian, Project Officer. The U.S. Environmental Protection Agency has funded, wholly or in part, the research described in this article. This article has not been subjected to Agency review. Therefore, it does not necessarily reflect the views of the Agency. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Contribution No. AED-02-061 of the Atlantic Ecology Division.

Address correspondence to John F. Paul, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency (Mail Drop B205-1), Research Triangle Park, North Carolina 27711, USA. E-mail: paul.john@epa.gov

TABLE 1 Summary of Recent Applications of GIS for Estuarine Monitoring and Assessment Research Conducted at the EPA/ORD Research Facility at Narragansett, Rhode Island

Application	GIS tool(s) used	Reference
Sample site selection	Spatial displays with multiple overlays, numerical algorithms, map projections, area clips	Holland (1990), Nelson et al. (1996), USEPA (2001, in press)
Support for field crew monitoring activities	Mapping with multiple overlays, map projections	Copeland et al. (1994), Strobel (2000), USEPA (2001)
Quality assurance of data	Spatial displays	Strobel and Valente (1995), USEPA (2001)
Spatial display of estuarine condition information	Spatial displays with multiple data layers, watershed delineation, area clips	Nelson et al. (1996), Paul and Morrison (1995), Paul et al. (1999), USEPA (1998) Weisberg et al. (1993),
Quantitative relationships between watershed metrics and estuarine sediment contaminant concentrations	Spatial analysis, export to statistical applications	Comeleo et al. (1996), Paul et al. (2002)
Wetlands analysis	Map overlays, spatial analysis	Wigand et al. (2001)
Land characterization data set accuracy assessment	Spatial analysis, export to statistical applications	Hollister et al. (submitted)

Environmental Protection Agency, Office of Research and Development (EPA/ORD) facility located in Narragansett, Rhode Island. The aspects of GIS, which set it apart from other technical tools, are explicit and accurate geographic referencing of data and linking attribute data to geographic referenced locations.

The intent of this brief overview is to provide a synopsis of these uses of GIS in the Northeast region of the U.S. The applications (summarized in Table 1) range from the selection of sampling sites to communication of results. The applications discussed here emphasize the geographic referencing capabilities of GIS and the linking of data with this geographic referencing, the capabilities that cannot be provided by graphic arts and non-GIS analysis tools.

Selection of Sampling Sites

Over the past few years, probability-based sampling designs have been increasingly used in estuarine monitoring and assessment (Paul et al. 1999; Summers et al. 1995). Historically, estuarine monitoring sites have been selected by judgement, for a definite purpose but without a probability basis for the selection (Olsen et al. 1999). What this implies is that the information acquired from these sites cannot be extrapolated to sites separate from the sites at which data were collected. This is appropriate if you were interested only in what was occurring at these sites. An example would be a gradient or transect study to test or validate indicators. However, research questions that include some estimate of the percent area of estuarine resources in a specified condition cannot be feasibly addressed using judgement sites (Holland 1990).

Sites that are selected using a probability or random approach are an unbiased representation of the sampled resource. This approach for sample site selection allows the extrapolation of information collected at a finite number of sites to the total resource, or the target population (Cochran 1987; Gilbert 1987). Here we refer to the resource about which we are interested in making inferences as the target population. What defines a probability design is that every element of the target population is available for sampling and has a nonzero probability of being selected (Overton 1993). The type of probability design that we have routinely used in estuarine monitoring and assessment research is site selection from a systematic grid laid over the resource (Stevens 1997). This type of design spatially distributes the sites over the extent of the estuarine resource.

Our use of GIS tools in site selection starts with acquiring GIS-compatible files that comprise the sample frame and putting these files into accurate geographic data sets. The sampling frame is the set of base maps, which are used for defining the target population from which the sample sites are selected. The sample frame data sets must exist at (or be converted to) a uniform scale in an equal area map projection, and should be reasonably accurate. USGS digital line graphs (DLGs) at 1:100K scale (USGS 1999) are used for most of our estuarine sampling frames. Our current implementation of the systematic design lays a tessellated hexagonal grid on the sample frame. This is followed by random selection of sites from within the estuarine area in each grid cell. The grid is tessellated to the spatial level necessary to provide the approximate number of desired sites over the target population. The origin and orientation of the systematic grid are chosen at random.

An example of a systematic hexagonal grid on a portion of the coast of Maine is shown in Figure 1. The target population, estuarine waters, is gray-scale in the figure. The probability of selection for a site with this design is inversely related to the area of estuarine resource within the grid cell. That is, the chance for selection of any individual element within a grid cell with small estuarine area is higher than a comparable element in a grid cell with a much larger estuarine area. Since one element is selected from each grid cell, the number of possible choices is smaller for the grid cell with the smaller estuarine area, thus resulting in a higher probability of any one element being selected. This design results in an unequal weighting, or variable inclusion probability, scheme for calculation of statistical properties such as means and variances. For example, the mean, $\bar{X}$, is calculated as

$$\bar{X} = \frac{\sum w_i x_i}{\sum w_i},$$

where w_i is the weight assigned to value x_i at site i. GIS allows accurate determination of the weighting factors (estuarine area within each grid cell), which become essential attributes associated with the site for subsequent analysis for inferences to the target population. The combination of GIS with accurate base maps helps reduce the uncertainty in the generation of site attributes, such as location and weighting factors.

Support for Field Crew Sampling Activities

Once sites are selected, maps are prepared for office reconnaissance to determine site accessibility and to identify property owners who must be contacted for permission to access the sites. Restricted access areas and sites that might be unsuitable for collection of data (e.g., fish trawling under a bridge or in waters too shallow) are also identified. Inaccessible sites are marked as such in the data files and become part of the unsampleable resource.

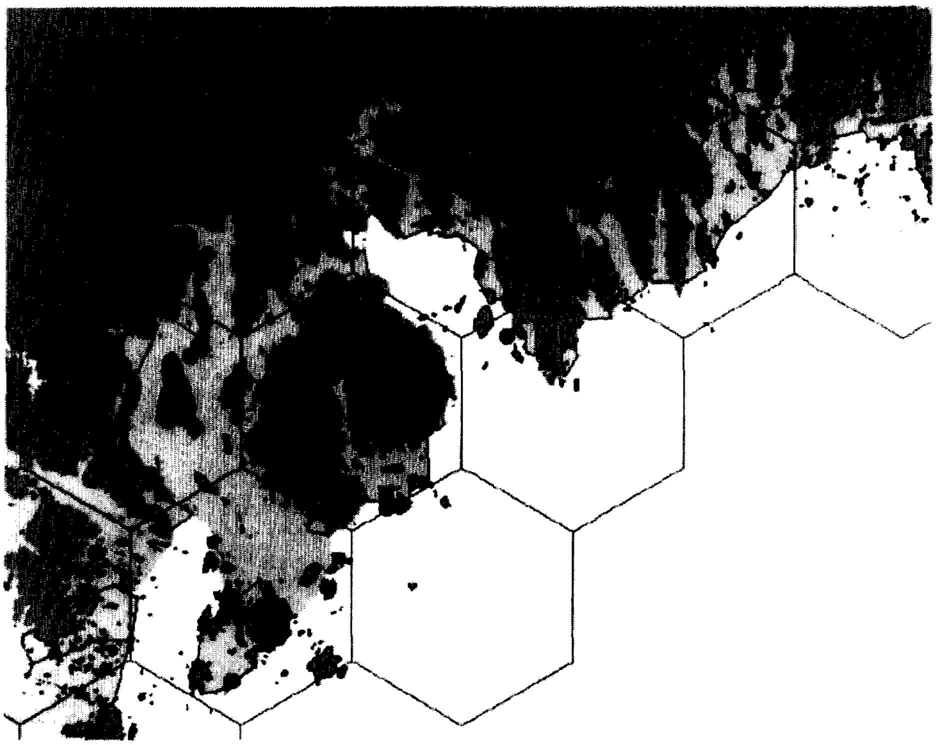

FIGURE 1 Example of hexagonal grid overlay on portion of estuarine waters along coast of Maine showing random site location selected for each grid cell.

Field maps are produced with overlays of boat ramp locations, dry ice vendors, sample shipment drop-off points for commercial shippers, and so on (Dunn and Bradstreet 2000). These maps are used for on-the-ground site reconnaissance and for sampling activities.

Electronic navigation charts (Maptech 2002), with overlays of the sampling grid and sample sites, are produced as navigation aids for field crews. Tidal charts are used by the field crews for navigating in shallow waters. The actual sampling is not tied to the stage of tide since the site visits are random over the tidal period. The use of GIS overlays, with up-to-date road coverages (ESRI 2000b) and navigation charts, provides efficient, accurate, up-to-date maps for navigation over land and water by the sampling crews.

Quality Assurance of Data

After collection activities by field crews are complete, the data generated need to be quality assured. This is necessary to provide documentation for the quality of the data. GIS is used for two aspects of quality assurance (QA). The first is to compare the actual locations that the field crews recorded for the sites visited (currently determined by Global Positioning System (GPS) units on the vessels (Strobel 2000), however, Loran C was also used in the early 1990s (Rosen et al. 1990)) with the planned locations (sites selected by the sampling design). Metadata associated with the site data include a description of the system used for positional location and a discussion of errors. Common sense is applied to locational accuracy requirements for water sites which are sampled from a moving platform anchored at a site. Maps are produced with planned and actual locations plotted, and separation distances between these two sets are calculated. Reviewing the maps easily picks up simple transcription errors (e.g., numbers transposed). A nominal separation distance between planned and actual locations is considered acceptable, but any site outside this allowable distance is checked to determine the cause of the discrepancy. Valid site locations, which were found to exceed the nominal separation distance, are flagged. The data from these sites must be used with caution since the site did not meet the QA requirements specified by the study and may not be representative of the site selected for sampling.

Simple range checking is done on all of the data. Outliers, values outside the observed range in the geographic area, are further examined and corrected if appropriate. If it is determined that these values are accurate, they are flagged in the database. This documents the process to assess the validity of the data values and assists in interpretation of results. The second aspect of QA where GIS is used is plotting the data (using color codes, symbol shapes, different thresholds, etc.) on maps to review the spatial distribution of the information. The spatial display of data provides a finer level of review than simple range checking. For example, the data are checked against known spatial gradients and clusters of locally similar values.

Spatial Display of Geographically Referenced Information

Analysis of the data can be of many forms. GIS is an important analysis tool for displaying the geographic extent and distribution of data values (Gentile et al. 1994; Paul et al. 1999). This is a first step in conducting spatial analyses. An initial form of this type was discussed in the prior section on QA, simple plotting of values on a map.

GIS tools permit determination of how the data values are distributed across the study area. That is, they have the ability to identify patterns. For example, Figure 2 is a spatial display of bottom water dissolved oxygen concentrations collected in the Mid-Atlantic estuarine waters in the summers of 1990–93 (Paul et al. 1999). Areas across the region where dissolved oxygen levels are of concern are readily apparent. Without using GIS to display information in spatial displays, the spatial patterns in the data would be more difficult to determine.

For some studies the spatial displays, as in Figure 2, may be adequate for analysis purposes. For other studies, multiple overlays of data may be necessary to identify valid statements explaining the data. For example, overlays with land use, habitat cover, and estuarine data can help generate possible links between the unacceptable conditions observed in the estuarine waters and likely causes of these conditions. The patterns observed in the spatial displays may generate hypotheses, which would be followed up with further research and testing. One needs to be cautious in the interpretation of patterns in spatial displays since relationships do not necessarily imply cause and effect.

One of the challenges in using data collected by different studies over a broad geographic area is how to combine the diverse data sets collected over different years, in different seasons, by distinct methods, and in relative isolation with regard to studies in neighboring systems. Paul and colleagues (2000) discuss how simple spatial displays were used to combine diverse data sets for use in a state of the environment report for Mid-Atlantic estuaries (USEPA 1998). For purposes of this state-of-the-environment reporting, the authors needed only characterize the condition of estuarine areas as good, fair, or poor. This low resolution of distinction, imposed on the data, made it possible to smooth over the small-scale discrepancies or uncertainties in the data sources for the spatial displays. Thus, use of spatial displays provided a procedure to incorporate data from diverse data sets that met the needs of the report.

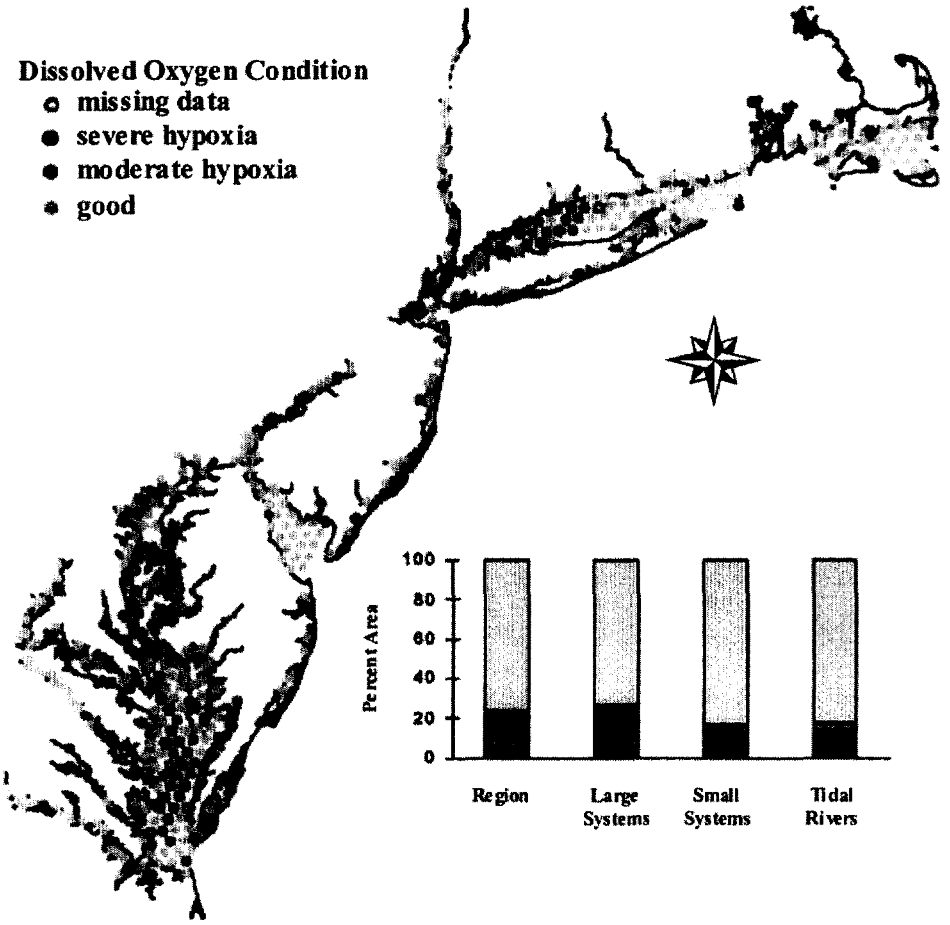

FIGURE 2 Spatial display of estuarine bottom water dissolved oxygen concentrations across the Mid-Atlantic region from summers of 1990–93 (from Paul et al. 1999).

Quantitative Spatial Analysis of Data

Quantitative spatial analysis of data (quantifying spatial patterns) requires more than just simply reviewing spatial displays as in the prior section. We want to quantify the spatial relationships that are visually observable in the data, and look for relationships that cannot be directly observed. GIS tools are particularly powerful for these analyses, since the geographic character of the data can be explicitly incorporated and used. This includes calculating metrics associated with different geographic areas and associating these metrics with specific estuarine areas. Specific examples are Comeleo and others (1996) and Paul and others (2002), where quantitative relationships were developed between landscape metrics and sediment contamination for small estuarine systems in the Mid-Atlantic region.

The initial step in these analyses was delineation of the watersheds for each of the systems. Two landscape metric categories used for analysis were land cover pattern and point source pollution input. Land cover pattern refers to the composition of watersheds with respect to the land cover types. GIS software was used to determine (1) the area of each land cover found within each watershed, and (2) the total annual outflow and pollution input from all point discharge sites located within each watershed. The latter is determined by clipping point source locations with watershed boundaries and then coupling with the relevant information (using the linked geographic referenced attribute data). For the final analysis, the results from the GIS analyses were combined with the appropriate estuarine data. Principle component analyses and stepwise multiple linear regression analyses were used to develop and test statistical models. The watershed metrics most strongly related with sediment metals levels were the percent area of nonforested wetlands (negative contribution), and percent area of urban land and effluent volume (positive correlations). Because of the different characteristics and dynamics of the estuaries across the Mid-Atlantic region, sediment characteristics and estuarine hydrology entered the statistical models to mitigate the influence of the landscape metrics on sediment contamination levels.

Communication of Results

An important aspect of any research study is communicating results to different audiences. Communication can take many different forms: printed media, oral presentations, poster presentations, and web-based material. Spatial display of information is particularly effective with a wide range of audiences for all of these communication approaches.

In an attempt to provide the information in a state of the estuaries report in an effective format, USEPA (1998) presented spatial displays (maps) showing condition of indicators across the entire region. To keep the message simple (the intended audience was the concerned public and environmental managers), the information portrayed on these maps was broken into three basic categories: good, fair, and poor. The colors green, yellow, and red, respectively, were used consistently to portray these categories for the various indicators.

For a more technical audience, Gentile and others (1994), Paul and others (1999), and Kiddon and others (in press) used spatial displays in their reports to convey the magnitude, extent, and distribution of biological, chemical, and physical indicators over a broad geographic region. Statistical analyses were used to quantify specific spatial patterns in data. For example, percent of geographic areas exceeding threshold values was calculated for estuarine systems across the region and for different categories of estuaries (such as small semienclosed systems and large, open-water areas). The combination of spatial displays with statistical estimates provides a more comprehensive description in support of conclusions.

Computer-assisted presentations at meetings were unusual a decade ago. The proliferation of personal computers and availability of user-friendly software have made PowerPoint™ presentations the standard presentation format at scientific meetings (for example, ERF 2001a; NWQMC 2002). GIS tools are effective at communicating complex information in the short period of time typically available at these meetings (generally, 15–20 minutes). But one should always be careful of not falling prey to the use of "chart junk" (Tuftke 1992), the hideous graphics that results from using all of the bells and whistles available in graphics software that obfuscates the visual interpretation of the information.

Poster presentations at scientific meetings often outnumber oral presentations (see, for example, ERF 2001b). Posters provide a different format than the single-slide-at-a-time of oral presentations; GIS tools can exploit the large-format detail that is lost in the smaller format of slides. An excellent example of what is possible by using GIS tools to prepare posters is ESRI (2000a).

Web-based dissemination of information is replacing the print copy. Our research programs routinely use this medium for providing background information on our programs, making available electronic copies of reports, and serving up data (USEPA 2002a, 2002b). Web-based interactive GIS mapping tools, such as ESRI products ArcIMS and MapObjects (ESRI 2002), provide user-friendly access that tailor requests to user-specific needs. This technology is still in its infancy.

Summary

GIS tools are now considered integral in estuarine monitoring and assessment research. The applications of GIS from our research in the Northeast region of the U.S. include the areas of sample site selection, support for field sampling activities, quality assurance of data, spatial display of geographic referenced information, quantitative spatial analysis of data, and communication of results to a wide range of audiences. While the widespread application of GIS tools has occurred, many of the tools are still in the initial phases of their development.

References

Cochran, W. G. 1987. *Sampling Techniques*. New York: John Wiley and Sons.

Comeleo, R. L., J. F. Paul, P. V. August, J. Copeland, C. Baker, S. S. Hale, and R. W. Latimer. 1996. Relationships between watershed stressors and sediment contamination in Chesapeake Bay estuaries. *Landscape Ecology* 11(5):307–319.

Copeland, J., C. Smith, S. Hale, P. August, and R. Latimer. 1994. EPA program monitors U.S. coastal environments. *GIS World* 7(8):44–47.

Dunn and Bradstreet. 2000. *Industry norms and key business ratios: Agriculture, mining, construction, transportation, communication, utilities*. Library ed. New York: Dunn & Bradstreet Credit Services.

Environmental Sciences Research Institute (ESRI). 2000a. *ESRI map book, Vol. 15, Applications of Geographic Information Systems*. Redlands, CA: ESRI Press. Interactive version available at http://www.esri.com/mapmuseum/mapbook_gallery/volume15/index.html

ESRI. 2000b. *ESRI data and maps 2000*. http://www.esri.com/data/datacd00.html. Description of available data sets at http://www.esri.com/library/whitepapers/pdfs/datamaps2000.pdf

ESRI. 2002. *ESRI online GIS store*. http://gisstore.esri.com/

Estuarine Research Federation (ERF). 2001a. *16th biennial meeting, information for PowerPoint users*. http://erf.org/erf2001/powerpoint.htm

ERF. 2001b. *16th biennial meeting, presentation schedule*. http://registration.outreach.usf.edu/erf1/presentations.asp

Gentile, J. H., K. J. Scott, J. F. Paul, and R. A. Linthurst. 1994. An ecological risk assessment case study: The role of monitoring in ecological risk assessment: An EMAP example. In *A Review of Ecological Assessment Case Studies from a Risk Assessment Perspective*, vol. 2 (pp 5-1–5-40). DC EPA/630/R-92/005. Washington, DC: Risk Assessment Forum, Office of Research and Development, U.S. Environmental Protection Agency.

Gilbert, R. O. 1987. *Statistical methods for environmental monitoring*. New York: Van Nostrand Reinhold.

Holland, A. F. 1990. *Near coastal program plan for 1990: Estuaries*. EPA/600/4-90/033. Narragansett, RI: Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

Hollister, J. W., J. F. Paul, P. V. August, and J. L. Copeland. Submitted. Assessing the accuracy of the National Land Cover Dataset at multiple spatial extents. Submitted to *Photogrammetric Engineering and Remote Sensing*.

Maptech. 2002. *Maptech digital chartkit*. http//www.maptech.com/water/digitalchartkit/index.cfm

National Water Quality Monitoring Council (NWQMC). 2002. *National monitoring conference, instructions for presenters*. http://www.nwqmc.org/presenterinformation.htm

Nelson, W. G., B. J. Bergen, S. J. Benyi, G. Morrison, R. A. Voyer, C. J. Strobel, S. Rego, G. Thursby, and C. E. Pesch. 1996. *New Bedford Harbor long-term monitoring assessment report: Baseline sampling*. EPA/600/R-96/097. Narragansett, RI: Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency.

Olsen, A. R., J. Sedransk, D. Edwards, C. A. Gotway, W. Liggett, S. Rathbun, K. H. Reckhow, and L. J. Young. 1999. Statistical issues for monitoring ecological and natural resources in the United States. *Environmental Monitoring and Assessment* 54:1–45.

Overton, W. S. 1993. Probability sampling and population inference in monitoring programs. In *Environmental Modeling with GIS*, edited by M. F. Goodchild, B. O. Parks, and L. T. Steyaert (pp. 470–480). New York: Oxford University Press.

Paul, J. F., R. L. Comeleo, and J. Copeland. 2002. Quantitative relationships between landscape metrics and sediment contamination for small estuarine systems in the Mid-Atlantic and Southern New England region of United States. *Journal of Environmental Quality* 31:836–845.

Paul, J. F., J. H. Gentile, K. J. Scott, S. C. Schimmel, D. E. Campbell, and R. W. Latimer. 1999. *EMAP-Virginian Province four-year assessment (1990–93)*. EPA/620/R-99/004. Narragansett, RI: Office of Research and Development, U.S. Environmental Protection Agency.

Paul, J. F., J. A. Kiddon, C. J. Strobel, B. D. Melzian, J. S. Latimer, D. J. Cobb, D. E. Campbell, and B. S. Brown. 2000. Condition of the mid-Atlantic estuaries: Production of a state of the environment report. *Environmental Monitoring and Assessment* 63(1):115–129.

Paul, J. F., and G. E. Morrison. 1995. Watershed stressors and environmental monitoring and assessment estuarine indicators for South Shore Rhode Island. In *National Conference on Environmental Problem-Solving with Geographic Information Systems, Cincinnati, Ohio, September 21–23, 1994*. USEPA Seminar Publication, EPA/625/R-95/004, September 1995, pp. 101–109.

Rosen, J. S., J. Beaulieu, M. M. Hughes, H. W. Buffum, J. L. Copeland, R. M. Valente, J. F. Paul, A. F. Holland, S. C. Schimmel, C. J. Strobel, J. K. Summers, K. J. Scott, and J. Parker. 1990. *Environmental monitoring and assessment program data base management system for near coastal demonstration project*. EPA/600/X-90/207. Washington, DC: Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

Stevens, D. L., Jr. 1997. Variable density grid-based sampling designs for continuous spatial populations. *Environmetrics* 8:167–195.

Strobel, C. J., and R. M. Valente. 1995. *Quality assurance report: EMAP-Virginian Province, 1990–93*. EPA/620/R-95/00. Narragansett, RI: Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

Strobel, C. J. 2000. *Coastal 2000-Northeast component: Field operations manual*. EPA/620/R-00/002. Narragansett, RI: U.S. Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division.

Summers, J. K., J. F. Paul, and A. Robertson. 1995. Monitoring the ecological condition of estuaries in the United States. *Toxicological and Environmental Chemistry* 49(1–2):93–108.

Tuftke, E. R. 1992. *The visual display of quantitative Information*. Chesire, CT: Graphics Press.

United States Environmental Protection Agency (USEPA). 1995. *National Conference on Environmental Problem-Solving with Geographic Information Systems, Cincinnati, Ohio, September 21–23, 1994*. EPA/625/R-95/004. Cincinnati, OH: National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

USEPA. 1998. *Condition of the Mid-Atlantic estuaries*. EPA/600/R-98/147. Washington, DC: U.S. Environmental Protection Agency.

USEPA. 2001. *Environmental monitoring and assessment program (EMAP): National coastal assessment quality assurance project plan 2001–2004*. EPA/620/R-01/002. Gulf Breeze, FL: Gulf Ecology Division, National Health and Environmental Effects Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.

USEPA. 2002a. *Environmental monitoring and assessment program home page*. http://www.epa.gov/emap

USEPA. 2002b. *Imprint of the past: The ecological history of New Bedford Harbor*. http://www.epa.gov/nbh

USEPA. In Press. *Mid-Atlantic Integrated Assessment-Estuaries, 1997-98 Summary Report. EPA/620/R-02/003. Narragansett, RI: Atlantic Ecology Division, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency.*

United States Geological Survey (USGS). 1999. *USGS digital line graph data.* http://edcwww.cr.usgs.gov/glis/hyper/guide/usgs_dlg

Wigand, C., R. Comeleo, R. McKinney, G. Thursby, M. Chintala, and M. Charpentier. 2001. Outline of a new approach to evaluate ecological integrity of salt marshes. *Human and Ecological Risk Assessment* 7(5):1541–1554.

Weisberg, S. B., J. B. Frithsen, A. F. Holland, J. F. Paul, K. J. Scott, J. K. Summers, H. T. Wilson, R. M. Valente, D. G. Heimbuch, J. Gerritssen, S. C. Schimmel, and R. W. Latimer. 1993. *Virginian Province demonstration project report, EMAP-Estuaries: 1990.* EPA-620/R-93/006. Narragansett, RI: Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.