Ensuring the Quality of Geographic Information System Data: A Practical Application of Quality Control

W. G. Campbell and *D. C. Mortenson*
NSI Technology Services Corp., Environmental Research Laboratory, U. S. Environmental Protection Agency, 200 SW 35th, Corvallis, OR 97333

ABSTRACT: Geographic Information Systems (GIS) are a valuable tool for many types of environmental analysis. Errors within GIS data, however, can limit the usefulness of GIS technology. To control and document the error introduced during data entry, we have instituted a series of Quality Control (QC) procedures for use within the U.S. Environmental Protection Agency's Direct/Delayed Response Project (DDRP). Central to our approach has been the use of formalized log sheets detailing the steps necessary for validating and digitizing mapped data. Additionally, we have evaluated the accuracy and precision of the data at specific stages of the data entry process. At critical stages, these formalized evaluations were independently repeated. We believe that the establishment of QC procedures within the DDRP has lead to very low error rate associated with GIS data entry. Our procedures and techniques described within this paper have other applications within the GIS community.

MUCH HAS BEEN WRITTEN about the need to recognize and, when possible, to improve data quality associated with Geographic Information Systems (GIS) (Jenks, 1981; Blakemore, 1983; Chrisman, 1982, 1984; Burrough, 1986; Otawa, 1987; Bedard, 1987; Bailey, 1988). There remains a general lack of information, however, on procedures to ensure accuracy and precision at different stages of GIS database development. This paper describes the steps that we have employed within the United States Environmental Protection Agency's (EPA) Direct/Delayed Response Project (DDRP) to control and document the quality of mapped data digitized or otherwise entered into a GIS. The DDRP is a large research effort designed to predict the long-term chemical response of surface waters to acidic deposition (Lee *et al.*, 1989; Campbell *et al.*, 1989; Church, 1989). Although digitization accuracy is but one aspect of the overall accuracy and precision of a spatial database, it is a critical component of database validity and defensibility.

Walsh *et al.* (1987) and Vitek *et al.* (1984) differentiated between inherent and operational errors associated with a GIS. Inherent error refers to uncertainty present within the source materials. Vegetation delineations, for example, are often inherently transitional and any attempt to delineate these areas is a simplification of reality (Seddon, 1971). Operational error represents uncertainties that are introduced during data input and machine processing within a GIS. Both inherent and operational errors introduce a degree of uncertainty that can result in a product of questionable quality (Vitek *et al.*, 1984). Bailey (1988) summarized the limiting role of error in a GIS by stating, "The machine processing of poor quality information will not produce better information upon which to base management decisions."

Controlling or recognizing inherent errors is a very difficult and, in some cases, impossible task. Burrough (1986) attributed the major source of unseen errors to natural spatial variation in the original data. MacDougall (1975) stated, "There is little that can be done with inaccuracy due to low purity of regions, other than prepare a map with higher purity standards." Considered more important than increasing purity within a region, MacDougall called for the compilers to estimate and present the accuracy in the assembly of the overlay. In the data quality section of the Proposed Standards for Digital Cartographic Data (DCDSTF, 1988), the authors essentially called for "truth in labelling." This allows the individual user to judge the fitness of the data for a particular use (Chrisman, 1984).

Operational uncertainty includes locational and attribute errors, as well as errors introduced during machine processing. Chrisman (1982) recognized that the largest potential errors in digital map processing occurred during digitization. Blakemore (1983) recognized that all digitized lines were prone to error. Error-reducing procedures, however, are not well documented. Otawa (1987) stated that operator experience in digitizing is likely to reduce errors associated with this procedure. He also noted, however, that accuracy checking is rarely performed in most digitizing projects. Jenks (1981) reviewed several studies and stressed the effect of user fatigue on digitization accuracy. Traylor (1979) noted that errors in digitizing were reduced by 50 percent through the use of positive feedback to the technician. In his study, the magnitude and direction of errors during digitization were automatically recorded. These errors were then analyzed and appropriate error reducing steps were taken. Bedard (1987) listed a series of steps that could reduce uncertainty within Land Information System data. These steps concerned the application of appropriate technical, procedural, organizational, and legal requirements, including good professional training, high precision standards, and inclusion of lineage in digital maps.

Within the DDRP, we have attempted to reduce the uncertainty of data entered into a vector-based ARC/INFO GIS* (ESRI, 1987). To accomplish this, we have initiated a series of Quality Control (QC) guidelines, procedures, and protocols for use during the data entry process.

BACKGROUND

PROJECT APPROACH

The DDRP approach is outlined below (see also Church, 1989). First, a statistically representative sample of watersheds was selected. The watersheds were characterized by field mapping and by using existing maps to document physical characteristics. Key soil types were selected for sampling, the sampling plan was implemented, and the soil samples were analyzed for

*Mention of brand names or commercial products does not constitute endorsement or recommendation for use.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 55, No. 11, November 1989, pp. 1613-1618.

0099-1112/89/5511–1613$02.25/0

physical and chemical characteristics. Watershed/soils data along with corresponding data on levels of acidic deposition and surface water chemistry were analyzed. Apparent relationships among these factors were examined and projections made for possible future effects of acidic deposition.

Site Selection

Two regions originally sampled as part of the EPA's National Surface Water Survey (NSWS) (Linthurst *et al.*, 1986; Messer *et al.*, 1986; Landers *et al.*, 1988) were identified for study by the DDRP (Lee *et al.*, 1989). These regions are the northeastern United States (Northeast) and the mountainous portion of the Southeast termed the Southern Blue Ridge Province. A sample of NSWS watersheds, stratified on alkalinity regions and NSWS sub-regions, were selected for study. Additional watersheds in the Mid-Appalachians and Northeast were selected at a later date, resulting in a total of 189 Northeast watersheds, 35 Southern Blue Ridge Province watersheds, and 36 watersheds in the Mid-Appalachians (Figure 1). All watersheds in the Northeast were lake-watershed systems; Mid-Appalachians and Southern Blue Ridge Province watersheds were stream-watershed systems. Watersheds ranged in size from 10 to 3,000 hectares.

Source Maps

The DDRP watersheds were characterized by compiling detailed watershed information on those characteristics thought important relative to the effects of acidic deposition. Soils, vegetation, and depth-to-bedrock were field mapped at a scale of 1:24,000 by the Soil Conservation Service (SCS) as was land use information for the Southern Blue Ridge Province. Land use information for the Northeast and Mid-Appalachians was interpreted from color infrared aerial photography by the EPA's Environmental Monitoring and Systems Laboratory (EMSL) in Las Vegas, Nevada (Liegel *et al.*, 1989). Streams were extracted from 1:24,000- or 1:62,500-scale topographic maps in the Northeast and field mapped by the SCS in the Southern Blue Ridge Province and Mid-Appalachians. Geology was extracted from appropriate state geology maps.

Many of the QC procedures that are mentioned within this paper have been implemented as the project has progressed.

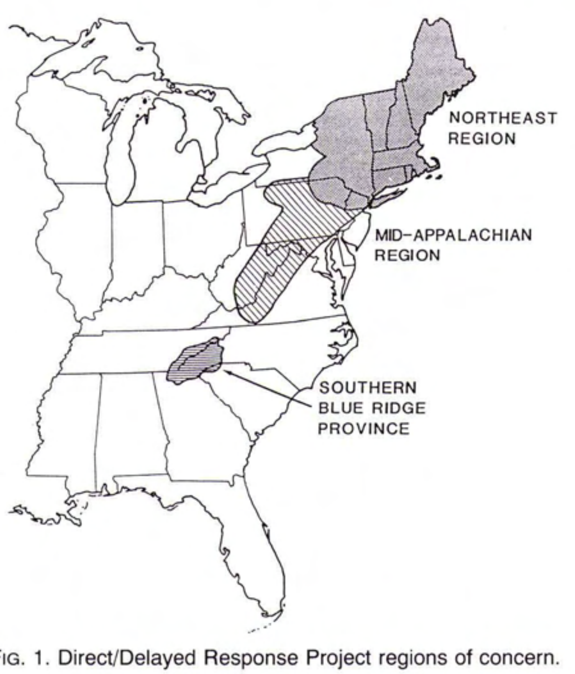

FIG. 1. Direct/Delayed Response Project regions of concern.

For example, certain procedures used in the Mid-Appalachian region were initiated following the discovery of errors associated with Northeast and Southern Blue Ridge Province data entry. Our discussion within this paper will focus on current QC procedures used within the DDRP. Specific QC procedures used in the Northeast and Southern Blue Ridge Province are described elsewhere (Mortenson, 1989a, 1989b).

Error Definition

To establish appropriate QC procedures, we first defined error associated with data entry. Attribute error was simply defined as error in transferring the attribute codes from the source material to the digital representation. This included missing codes or multiple codes per polygon. The accuracy of mapped polygon codes relative to field conditions is addressed elsewhere (Lee *et al.*, 1989; Liegel *et al.*, 1989). Error within a digitized line segment was defined as any visible deviation of the digitized line from the source line segment. As long as the digitized line segment fell within the boundary of the drafted line segment and contained no inadvertent polygons, the digitized line segment was assumed to be correct. Error associated with line segment digitization was entirely dependent on the accuracy and precision of the source material (e.g., width of the drafted line, purity of regions, etc.). Errors in line segment digitization could, thus, be easily identified by overlaying the digitized and drafted line segments on a light table and identifying the existence of areas between the lines where light was visible. Although numerous authors refer to deviations from the theoretical centers of the source line segments as error (Jenks, 1981; Blakemore, 1983; Chrisman, 1982; Burrough, 1986), checking for this type of error is difficult and expensive in an applied setting. Furthermore, given the inherent uncertainty in many of the watershed variables (e.g., soils), small deviations from the center of the source line segments would clearly be insignificant.

QUALITY CONTROL

Central to our approach has been the use of formalized log sheets to record the steps necessary to validate and digitize mapped data. The use of log sheets during the digitization process served several purposes. First, each technician was required to sign and date the log sheet following successful completion of each step. This helped to ensure consistency and accountability. Secondly, the signed log sheet became part of the permanent record of the project and, therefore, provided key documentation. Finally, because the log sheets identified a responsible party, we had the ability to backtrack when systematic errors or problems were discovered. In addition to log sheets, accuracy and precision of the mapping products were formally evaluated at various stages. At critical stages, the evaluations were independently repeated by a second technician.

Pre-Digitization Procedures

Prior to data entry, the source maps were checked for consistency, accuracy, and completeness. The source maps were then adjusted or corrected prior to automation. Formalized log sheets were used to validate these procedures (Figure 2). The adjustment of source materials to make them agree is similar to the Integrated Survey work in Australia (Christian and Stewart, 1968; Mabbutt, 1968) as well as Integrated Terrain Unit Mapping as described by Dangermond *et al.* (1982). These techniques define landscape units on the basis of a combination of factors (e.g., soils, terrain) rather than treating them individually. Quality Assurance (QA)/QC procedures were also implemented by the SCS during field mapping and are described elsewhere (Lee *et al.*, 1989).

Watershed Delineation. There is always some degree of subjectivity associated with the delineation of watersheds. This

DDRP SOIL SURVEY
MAP CHECKING CHECKLIST
GEOGRAPHIC RESEARCH

Watershed ID__________ Watershed Name, Co., State________________
Name(s) of Reviewer(s)______________________________ Date________
Mappers____ Date Mapped________

1.Have all the map overlays arrived at CERL:

SCS
___soils ___veg ___geo ___dep ___drainage ___transects

LEMSCO
___land use ___detailed wetlands ___drainage

2.Are tic marks present and accurate?

DISCUSSION AND RECOMMENDED FOLLOWUP - Registration

3.Are SCS watershed delineations consistent?

4.Do SCS delineations follow NSWS delineations?

5.Do LEMSCO delineations follow SCS and/or NSWS delineations?

DISCUSSION AND RECOMMENDED FOLLOWUP - Watershed delineations

6.Do SCS streams agree with USGS blue lines?

7.Do SCS delineations follow topographic features?

DISCUSSION AND RECOMMENDED FOLLOWUP - Drainage

FIG. 2. An example of a log sheet used during pre-digitization Quality Control. This form details the steps used to check map registration, watershed boundary delineations, and drainage.

became particularly evident in the course of our project. Watersheds were first delineated based on contour crenulations on 1:24,000- or 1:62,500-scale topographic maps. The watershed delineations were then sent to the SCS and EMSL for mapping. During mapping, individual mappers sometimes changed from the predetermined topographic delineation based on ancillary evidence derived from air photos or field information. These subjective changes were particularly evident in the low-lying areas of the Northeast (e.g., the Massachusetts coastal plain) and in areas that were only covered by older and less accurate 1:62,500-scale topographic maps. In these areas, defining the "correct" boundary based on coutour crenulations was almost impossible (see also Liegel *et al.*, 1989).

There were potentially three different watershed delineations: the preliminary estimate of the watershed delineation based on topographic maps, the field delineation, and the photo-interpreted delineation. We first checked if the field mapped delineation followed the topographic delineation. Next, we compared all delineations for consistency (e.g., were the same ridgetops followed, was the outlet of the watershed consistently located, etc). If the mapped delineations followed the topographic delineations and were consistent with each other, the delineation was accepted. If there were large differences between the delineations (e.g., watershed outlet not consistently located, inclusion or exclusion of sub-basins, etc.), we assumed the field mapped version to be correct as long as the SCS had a legitimate reason to adjust the boundary. Legitimacy was confirmed by discussing any "problem" areas with the field mappers. The land use maps were then adjusted or re-mapped to fit the final boundary.

Watershed Consistency. As described previously, all layers were first checked for consistency in watershed delineations and corrections were made. A second source of inconsistency was in the definition of water or lake boundaries. Errors within the SCS mapping layers were first identified, problem areas were discussed with SCS, and appropriate corrections were made. Three inherent sources of variability, however, could result in different SCS versus EMSL water body delineations. These sources included (1) different air photos used by EMSL and SCS mappers (original NE only), (2) differences in mapping resolution of wetlands - EMSL mappers delineated wetlands down to one acre while the SCS used a six-acre minimum resolution (the minimum SCS delineation was reduced to 2 acres in the M-A and a portion of the NE watersheds), and (3) individual mappers produced different water body interpretations due to the inherent limitations of the particular mapping technique (e.g., field versus photo-interpreted). Because of this inherent variability in the delineation of water bodies, we did not attempt to reconcile SCS versus EMSL lake delineations.

Mapping Completeness. All source maps were first visually scanned for completeness (e.g., existence of polygon codes) and obvious errors (e.g., missing line segments). We did not spend an inordinate amount of time with this task as these errors were more efficiently identified during subsequent QC procedures.

Mapping Registration. Registration marks are used to transform digital maps to ground coordinates. Individual layers were first checked for registration to a topographic map. Next, each individual layer was manually overlaid with other layers and consistency was examined and corrected where appropriate.

Map Unit Registration. Map unit registration refers to how well the individual map units correlate with topographic and other physical features. This has been one of the more difficult areas we have dealt with during the project. Many of our analyses depend on the ability to vertically integrate the various layers. Without adequate map unit registration, this can become a futile exercise.

To check map unit placement, we compared the mapped information with appropriate topographic maps. We first overlaid the soils and depth-to-bedrock source maps onto the topographic map. Next, we checked if ridgetop soils followed topographic ridgetops and whether valley-bottom soils followed stream channels. If the mapped features followed the topographic features, map unit registration was accepted. We followed the same general procedures for vegetation as well, although we relied primarily on lowland, riparian, and open vegetation patterns and their correspondence with topographic features. If map unit registration was judged inadequate, the individual map layers (e.g., soils) were re-drawn to better fit topographic features.

DIGITIZATION PROCEDURES

QC checks instituted during the digitization process addressed three major goals: digitization consistency, line segment accuracy, and attribute accuracy. As with pre-digitization procedures, the use of formalized log sheets was central to our approach.

Digitization Consistency. We ensured digitization consistency by using log sheets and by implementing specific technical guidelines for use in the digitization process. Formalized log sheets were used during both line segment digitization and attribute entry (Figures 3 and 4, respectively) to ensure consistent data entry, to provide key documentation, and to provide a system of accountability.

Two technical guidelines were also used during the digitization process to increase consistency. First, we used a minimum acceptable Residual Mean Square (RMS) error during the transformation process. The RMS error is a measure of the accuracy of tic registration (ESRI, 1987). In general, the minimum acceptable RMS error was 0.003 inch, although we occasionally accepted higher RMS values when using poor quality source maps. Second, a template layer containing the watershed and water body boundaries was digitized using the soils layer as a guide. Line segments and attributes were then added to the template coverage for each of the individual SCS layers. This helped to ensure consistent watershed and water body boundaries for all layers.

Line Segment Digitization. The steps used in line segment digitization are depicted in Figure 3. During digitizing, all line segments were purposely extended as overshoots to create "dangling chains" (Chrisman, 1987). The overshoots were then automatically deleted during the building of topological structure. Following digitization, plots were made using an internal editing feature of the ARC/INFO software. These plots depicted polygon errors including unclosed polygons, unlabeled polygons, or polygons with more than one label point. Identified errors were corrected before continuing. A new plot displaying all digitized line segments and labels was then made at the same scale as the manuscript maps. The plot was overlaid with the manuscript maps onto a light table. If any light showed through between the digitized line segment and the drafted line, the line segment was corrected and the polygon error check was repeated.

Attribute Entry. The steps used in attribute entry are shown in Figure 4. First, the attributes for each map unit were entered into a text file and visually scanned for obvious errors. Corrections were then made before proceeding to the next step. The text file containing the attributes was loaded into an ARC/INFO database "template" file containing the appropriate item definitions. The template file was merged with the coverage, visually scanned for any obvious errors, and corrected where appropriate. We performed a more thorough evaluation of attribute accuracy following digitization.

Post-Digitization Procedures

Post-digitization QC procedures included checks on coverage accuracy and ground coordinate registration. Coverage accuracy was evaluated through two independent checks of edit plots and by examining the regional consistency and validity of attribute codes. Projection accuracy checks included comparisons within our data and comparisons between our digitized data and other independent data.

Coverage Accuracy. Final plots depicting line segments and attributes of each coverage were first generated. These plots were then compared with the original source maps over a light

```
DIRECT/DELAYED RESPONSE PROJECT - COVERAGE AUTOMATION LOG

WATERSHED NO.__________DATE__________                INITIALIZE UPON
                                                     COMPLETION
                                                     ____________

1.   $ SET DEF [DDELAY.------]

2.   $ ARC

3.   ARC: ADS LANDDG                                 LANDDG_______
          Digitize tics, watershed boundary,
          all water bodies, and all land use polygons.

4.   ARC: CLEAN LANDDG LANDCN .25                    LANDCN_______

5.   ARC: EDITPLOT LANDCN LAND.PLT                   LAND.PLT_____
          Check for polygon errors

6.   ARC: ARCEDIT                                    LANDCN_______
          Make corrections, as needed.
          Repeat steps 4-6, as needed.

7.   ARC: COPY LANDCN LANDUSE                        LANDUSE______
```

FIG. 3. An example of a log sheet used during line segment digitization. This form details the required steps for digitization of land use line segments.

```
DIRECT/DELAYED RESPONSE PROJECT - DATA ENTRY LOG

WATERSHED NO.__________DATE__________                INITIALIZE UPON
                                                     COMPLETION
                                                     ____________

1.   $ SET DEF [DDELAY.------]

2.   $ COPY [DDELAY]BASE.DAT LAND.DAT

3.   $ VP LAND.DAT                                   LAND.DAT_____
          type in data
          <ctr>Z

4.   $ ARC

5.   ARC: INFO                                       LANDTAB______
     USER NAME> ARC
     ENTER COMMAND> ADIR [DDELAY.SKELETON1.INFO]
     ENTER COMMAND> TAKE ARC *
     ENTER COMMAND> SEL LANDTAB
     ENTER COMMAND> ADD FROM [DDELAY.------]LAND.DAT
     ENTER COMMAND> LI - check data
     ENTER COMMAND> Q STOP

6.   JOINITEM LANDUSE.PAT LANDTAB LANDUSE.PAT LANDUSE-ID LANDUSE-ID
                                                     LANDUSE.PAT___

7.   ARC: INFO                                       LANDUSE.PAT___
     USER NAME> ARC
     ENTER COMMAND> SEL LANDUSE.PAT
     ENTER COMMAND> LI - check .PAT file
     ENTER COMMAND> Q STOP
```

FIG. 4. An example of a log sheet used during attribute entry. This form details the required steps for entering land use attributes.

table and checked for accuracy. If any light passed between the digitized line segment and the drafted line, the digitized line segment was corrected to match the drafted line segment, and the necessary QC procedures were repeated. If the line segments were judged to be correct, each individual coverage attribute was then checked against the source map for accuracy and corrected as needed. This entire procedure was performed independently by two individuals. If the coverage was judged to be correct, the individuals were required to sign the plot indicating acceptance. As a final check, attributes for all watersheds were written to a file, sorted, and independently checked for consistency and validity. This final sorting and checking of the master file helped to identify non-obvious errors such as substitution of the letter "O"with the number "0".

Projection Accuracy. We used a series of procedures to accurately transform the coverages into ground coordinates, including comparing (1) "projected" coverages with source map, (2) "projected" versus "non-projected" coverages, (3) land use and SCS projections, and (4) digitized mapped data with independently obtained data.

First, the coverages were converted into UTM coordinates. The projected coverages were then overlaid with the source map and checked for registration and reasonableness of fit. The position of projected watersheds was then compared with coordinates of the appropriate lake or stream as documented by the NSWS (Linthurst *et al*., 1986; Messer *et al*., 1986; Landers *et al*., 1988). The NSWS point location data represented the lake and stream locations estimated independently from 1:24,000- or 1:62,500-scale topographic maps. Next, the original digitized ("non-projected") coverages were overlaid with the "projected" coverages and checked for consistency in area representation. Watershed areas were then calculated and compared for the "projected" versus "non-projected" coverages. Watersheds with area variations of greater than five percent were flagged and visually re-examined. To detect locational errors or any major differences in watershed or lake delineations, the SCS base coverage was then visually compared to the EMSL coverage. Finally, watershed area was calculated and compared for the

SCS versus land use coverages. Watersheds with variations of greater than five percent were flagged and visually re-examined.

RESULTS

Map quality is always difficult to ascertain. The question always remains as to how well the QC procedures worked. QC procedure evaluation can be accomplished by referencing the second QC check of the "final" plot. The second check for the additional Northeast watersheds (44 watersheds ranging in size from 25 to 700 hectares) was completed by one individual. Soil mapping information for these watersheds consisted of 1,212 mapping units. During the second QC check, the entire population of polygon codes and line segments was checked for accuracy by overlaying the completed coverage onto a light table and comparing this with the source map. This check indicated that less than one percent of the attribute codes were in error. At the same time, all digitized line segments were scanned for accuracy. Error was found in only one line segment out of 3,737. All line segments and attribute codes found in error were then corrected. Although we checked the entire population, we can not assume that the resulting attribute codes or digitized line segments are error-free. The first QC plot check should, theoretically, have caught all errors.

Following plot checking, all attribute codes were written to a file, sorted, checked for consistency, and compared with a master list of valid codes. This check revealed that one of 1,212 attributes was in error.

DISCUSSION

Results obtained from the DDRP will likely have a significant influence on "acid rain" leglislation. Our impetus to initiate QC during the digitization process was partially a function of the overall importance and visibility of the project. Our techniques, however, have other applications in the GIS community.

There are many different types of spatial data and, hence, many potential requirements for digitization. We do not imply that our QC procedures could be applied universally. There are important distinctions between our data and other spatial data. First, because we work exclusively with a large number of relatively large-scale watersheds, specific digitization procedures and guidelines were inherently useful. Secondly, as our watersheds were not adjacent, there was no need for horizontal integration. Edge matching procedures, for example, were not needed.

In addition to the application of QC procedures, we believe that other factors may have contributed to the low overall error rate. First, most maps were checked for line segment accuracy immediately following digitization of a watershed. This provided immediate feedback to the individual, and thus aided in the identification and correction of systematic errors. Second, individuals were not hired as digitizers; rather, all had other duties within the project from cartographic design to data analysis. In our judgement, this served to decrease the error rate associated with digitization by giving individuals a greater sense of purpose and ownership. This also contributed to a very low turnover rate of personnel, resulting in a high level of digitizing experience. Finally, each individual digitized no longer than four hours per day, minimizing user fatigue.

Because of our low overall error rate, it appears that we were successful in identifying and correcting errors during the data entry process. Our coverages, however, remain no more accurate than the source materials. The inherent uncertainty that exists within the mapped features limit the overall accuracy and validity of the information used within the DDRP. We have, however, reduced many of the errors that are commonly associated with entry of spatial data and, therefore, the application of QC within our project should increase the validity and defensibility of our data.

ACKNOWLEDGMENTS

We thank G. Bishop, S. Pierson, and C. Kaffke for their strong contributions to all phases of GIS development and utilization within the DDRP. Without their contributions, this paper would not have been possible. We thank M.R. Church for project leadership and general support of this paper. We thank A. Herstrom, A. Kinney, D. Nesbitt, and J. Omernik for their work in establishing, managing, and maintaining the GIS. We thank G. Griffith, L. Ellingson, M.R. Church, G. Bishop, S. Pierson, and C. Savonen for providing helpful reviews of this document. Finally, we thank three anonymous reviewers for constructive and helpful comments throughout the document. This research is part of the Direct/Delayed Response Project, part of the National Acid Precipitation Assessment Program.

REFERENCES

Bailey, R. G., 1988. Problems with using overlay mapping for planning and their implications for Geographic Information Systems, *Environmental Management*, Vol. 12, No. 1, pp. 11–17.

Bedard, Y., 1987. Uncertainties in Land Information Systems databases, *Proceedings, Eight International Symposium on Computer-Assisted Cartography*, Baltimore, pp. 175–184.

Blakemore, M., 1983. Generalization and error in spatial databases, *Proceedings, Sixth Annual Symposium on Automated Cartography*, Ottawa, pp. 313–322.

Burrough, P. A., 1986. *Principals of Geographical Information Systems for Land Resources Assessment*, Oxford University Press, New York, 193 p.

Campbell, W. G., M. R. Church, G. D. Bishop, D. C. Mortenson, and S. M. Pierson, 1989. The role for a Geographic Information System in a large environmental project, *International Journal of Geographical Information Systems* (in press).

Chrisman, N. R., 1982. A theory of cartographic error and its measurement in digital databases, *Proceedings, Fifth International Symposium on Computer-Assisted Cartography*, Crystal City, pp. 159–168.

———, 1984. The role of quality information in the long-term functioning of a Geographic Information System, *Cartographica*, Vol. 21, No. 2, pp. 79–87.

———, 1987. Efficient digitizing through the combination of appropriate hardware and software for error detection and editing, *International Journal of Geographical Information Systems*, Vol. 1, No. 3, pp. 265–277.

Christian, C. S., and G. A. Stewart, 1968. Methodology of integrated survey: aerial surveys and integrated studies, UNESCO, Paris, pp. 233–280.

Church, M. R., 1989. Predicting the future long-term effects of acidic deposition on surface water chemistry: the Direct/Delayed Response Project, *EOS, Transactions of the American Geophysical Union*, Vol. 70, pp. 801–813.

Dangermond, J., B. Derrenbacher, and E. Harnden, 1982. *Description of Techniques for Automation of Regional Natural Resource Inventories*, Environmental Systems Research Institute, Redlands, California.

DCDSTF, 1988. The proposed standard for digital cartographic data, *The American Cartographer*, Vol. 15, No. 1, pp. 129–135.

ESRI, 1987. *ARC/INFO Users Guide*, Environmental Systems Research Institute, Redlands, California.

Jenks, G. F., 1981. Lines, computers, and human frailties, *Annals of the Association of American Geographers*, Vol. 71, No 1, pp. 1–10.

Landers, D. H., W. S. Overton, R. A. Linthurst, and D. F. Brakke, 1988. Eastern Lake Survey: regional estimates of lake chemistry, *Environmental Science and Technology*, Vol. 22, pp. 128–134.

Lee, J. J., D. L. Lammers, M. J. Johnson, M. R. Church, D. L. Stevens, D. S. Coffey, R. S. Turner, L. J. Blume, L. H. Liegel, and G. R. Holdren, 1989. Watershed surveys to support an assessment of the regional effects of acidic deposition on surface water chemistry, *Environmental Management*, Vol. 13, No. 1, pp. 95–108.

Liegel, L. H., M. R. Church, D. L. Cassell, W. G. Campbell, D. J. Bogucki, G. K. Gruendling, and E. B. Allen, 1989. Using color infrared areal photography in regional acid precipitation research, *Photogrammetric Engineering and Remote Sensing* (in review).

Linthurst, R. A., D. H. Landers, J. M. Eilers, D. F. Brakke, W. S. Overton, E. P. Meier, and R. E. Crowe, 1986. Characteristics of lakes in the eastern United States. Volume 1: *Population Descriptions and Physio-Chemical Relationships*, U.S. Environmental Protection Agency, EPA-600/4-86-007a, 136 p.

Mabbutt, J. A., 1968. Review of concepts of land classification, *Land Evaluation* (G. A. Stewart ed.), MacMillan, Melbourne, pp. 11–28.

MacDougall, E. B., 1975. The accuracy of map overlays, *Landscape Planning*, Vol. 2, pp. 23–30.

Messer, J. J., K. N. Eshleman, S. M. Stambaugh, and P. R. Kaufmann, 1986. *National Surface Water Survey Phase I - Pilot Survey*, U.S. Environmental Protection Agency, EPA/600/4-86/026, 179 p.

Mortenson, D. C., 1989a. *Geographic Information System Documentation of Watershed Data for Direct/Delayed Response Project - Northeast Database*, U.S. Environmental Protection Agency, EPA/600/3-89/001, 19 p.

———, 1989b. *Geographic Information System Documentation of Watershed Data for Direct/Delayed Response Project - Southern Blue Ridge Province Database*, U.S. Environmental Protection Agency, EPA/600/3-89/002, 16 p.

Otawa, T., 1987. Accuracy of digitizing: overlooked factor in GIS operations, *Proceedings, GIS'87*, San Francisco, pp. 295–299.

Seddon, B., 1971. *Introduction to Biogeography*, Harper and Row, New York, 220 p.

Traylor, C. T., 1979. *The Evaluation of a Methodology to Measure Manual Digitizing Error in Cartographic Data Bases*, University of Kansas (unpublished doctoral dissertation).

Vitek, J. D., S. J. Walsh, and D. R. Butler, 1984. Accuracy in Geographic Information Systems: an assessment of inherent and operational errors, *Proceedings, PECORA IX*, pp. 296–302.

Walsh, S. J., D. R. Lightfoot, and D.R. Butler, 1987. Recognition and Assessment of Error in Geographic Information Systems, *Photogrammetric Engineering and Remote Sensing*, Vol. 53, No. 10, pp. 1423–1430.

Forthcoming Articles

D.S. Bhargava and *Dejene W. Mariam,* Spectral Reflectance Relationships to Turbidity Generated by Different Clay Materials.
Thomas W. Becker, Teaching Remote Sensing as Public Classroom Instruction.
P.H. Biggs, C.J. Pearce, and *T.J. Westcott,* GPS Navigation for Large-Scale Photography.
W.M. Ciesla, C.W. Dull, and *R.E. Acciavatti,* Interpretation of SPOT-1 Color Composites for Mapping Defoliation of Hardwood Forests by Gypsy Moth.
Li Deren and Shan Jie, Quality Analysis if Bundle Block Adjustment with Navigation Data.
Keld S. Dueholm, Multi-Model Stereo Restitution.
Manfred Ehlers, Mark A. Jadkowski, R. Richard Howard, and *David E. Brostuen,* Application of SPOT Data for Regional Growth Analysis and Local Planning.
Eric M. Eliason and *Alfred S McEwen,* Adaptive Box Filters for Removal of Random Noise from Digital Images.
Wolfgang Faig and *Tian-Yuan Shih* Should One Consider Combining Kinematic GPS with Aerial Photogrammetry?
Wolfgang Faig, Tian-Yuan Shih, and *Gang Deng,* The Enlarger-Digitizer Approach: Accuracy and Reliability.
John G. Fryer and *Derek J. Goodin,* In-Flight Aerial Camera Calibration by Photography of Linear Features.
Lisa R. Gaddis, Peter J. Mouginis-Mark, and *Joan N. Hayashi,* Lava Flow Surface Textures: SIR-B Radar Image Texture, Field Observations, and Terrain Measurements.
Joshua S. Greenfeld and *Anton F. Schenk,* Experiments with Edge-Based Stereo Matching.
R.J. Hall and *P. Hiscocks,* A Computer-Based Cameras Control System.
Marsha Jo Hannah, A System for Digital Stereo Image Matching.
Leigh Harrington, Mark Rivard, William Zink, and *Nancy Cobos,* Sample Surveys that Use Imagery with Varying Area Coverage.
Raymond J.Hintz and *Mike Z. Zhao,* Considerations in the Implementation of Aerotriangulation with GPS Derived Exposure Station Positions.
G. Keel, H. Jones, G. Lachapelle, R. Moreau, and *M. Perron,* A Test of Airborne Kinematic GPS Positioning for Aerial Photography.
Mathew Krogulecki, A Prototype Decision Guide and Audit Log for Preparation of Spatial Databases.
Nina Siu-Ngan Lam, Description and Measurement of Landsat TM Images Using Fractals.
Royal Lee, Po-Chiang Lu, and *Wen-Hsiang Tsai,* Robot Location Using Single Views of Rectangular Shapes.
C.P. Lo and *W. Edward Noble, Jr.,* Detailed Urban Land-Use and Land-Cover Mapping Using Large Format Camera Photographs: An Evaluation.
Kim E. Lowell, Differences Between Ecological Land Type Maps Produced Using GIS or Manual Cartographic Methods.
Dean C. Merchant and *Robert L. Tudhope,* Aerial Photo System Calibration Over Flat Terrain.
William R. Niedzwiedz, Assessing Permit Compliance in Residential Areas Using Color 35mm Aerial Photography.
G. van den Brink, P.G. Schwarz, and *G.J. van der Wildt,* A New Testing Procedure for Recruitment of Photogrammetrists.
Stephen J. Ventura, Conversion of Automated Geographic Data to Decision-Making Information.
Torbjorn Westin, Precision Rectification of SPOT Imagery.
David S. Wilkie, Performance of a Backpack GSP in a Tropical Rain Forest.

NEW SUSTAINING MEMBER NUS CORPORATION

Comprehensive service from a single source. NUS Corporation is an international enviromental and engineering consulting firm with more than 1900 employees, located in 25 offices nationwide. NUS provides consulting, engineering, training, hazardous waste management, and laboratory services for clients whose operations impact broad environmental, health, safety, and energy concerns. An integral part of these services is the application of GIS technology.

For more than 25 years, NUS has been a national leader in environmental consulting. Our recent enviromental assessment programs have supported the restart of a nuclear production reactor, the site of a major nuclear waste facility, and the programmatic compliance for the Strategic Defense Initiative's technology development programs.

We combine advanced technologies modeling with state-of-the-art field testing and real time computerized environmental monitoring systems to meet planning and licensing requirements.

Our experience in analytical modeling is complemented by advanced GIS analysis and mapping, to provide a provide a dynamic visual tool for evaluating existing and planned facilities. With the ESRI ARC/INFO GIS and ERDAS image processing systems, NUS has at its disposal the best GIS capability available.