The Design and Implementation of an Integrated Geographic Information System for Environmental Applications

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Abstract

Environmental monitoring and restoration at the U.S. Department of Energy's Savannah River Site (SRS) requires efficient access to large amounts of diverse spatial information. These geographic information system (GIS) and remotely sensed data are related to both physical and man-made features. In order to handle this task, the Environmental Sciences Section (ESS) of the Westinghouse Savannah River Company (WSRC) created the Environmental Data Atlas (EDA) that uses spatial keys to link all data sources to a common geographical data base. Furthermore, it was important that all of the data be readily accessible on the desktop of scientists regardless of the type of computer platform they used. This paper describes the creation of a comprehensive computing environment that utilizes a geographical data browsing system as the core for meeting these requirements. It also describes how bibliographic search and aerial photography browsing functions were incorporated into the system. Finally, it describes a sophisticated modeling system that has been integrated into the system to support site selection activities. By taking advantage of the latest advancements in geographical data browsing systems, fourth generation procedural programming languages, and network communications, the integrated system represents an important step in the evolution of GIS.

Introduction

The rapid development of spatial information technology has promoted the use of geographically related data in a large variety of environmental applications within the Environmental Sciences Section (ESS) of the U. S. Department of Energy's Savannah River Site (SRS). Over the past 50 years, environmental data for the 777 square kilometres of SRS have been used in various research and programmatic activities. Representative projects have included facility site selection, industrial discharge, National Environmental Policy Act (NEPA) support, environmental risk assessment, and analysis of waste sites for restoration or closure. Many of these projects have employed remote sensing and geographic information system (GIS) technology to characterize the environment, and to monitor changes related to the operations at the site, (i.e., Jensen *et al.*, 1983; Mackey *et al.*, 1991). The data needed to address these problems are distributed throughout many sections of SRS. In order to more efficiently utilize current technology, scientists within SRS desire to easily access these data and perform analysis using their personal desktop computers. In order to accomplish these objectives, the Environmental Data Atlas (EDA) system was developed. The EDA represents one of the first operational systems to utilize a geographical data browser as the core for a comprehensive system that incorporates specialized data retrieval functions and a sophisticated GIS modeling system.

This paper is organized into three sections. The first section explains how the EDA was created and the design considerations relating to user interfaces and network access. It describes the design philosophy that took advantage of current hardware and software technology to address some of the limitations of other systems. The second section describes two management tools to handle bibliographic information and to locate aerial photography. The final section describes how the EDA is linked to a full featured GIS to assist in important spatial decision support activities at the site.

Design Considerations

Users and Requirements

The major system design considerations for the EDA were based on the need to provide a robust but user-friendly set of spatial data handling, data retrieval, and modeling functions that would operate on a wide range of computer systems. Based on a survey of user requirements of the Environmental Sciences Section, the specific design criteria were

- Inclusion of all forms of spatial data, including CAD drawings, and various forms of raster and vector GIS data;
- Inclusion of various sources of remotely sensed data, including satellite and aircraft based scanning systems, and conventional aerial photography;
- Integration of digital elevation models;
- True client server network operation serving Intel, Macintosh, and UNIX platforms;
- Integration of multi-media database extensions;
- Spatially oriented bibliographical retrieval system;

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- Aerial photography browsing system; and
- Integrated site selection modeling system.

Although these requirements were identified by environmental scientists at a major environmental site, the list represents a fairly common set of current user needs. Even at SRS the community of GIS users is constantly expanding. Burrough and Frank (1995) provide a useful classification of GIS users. According to their taxonomy, the environmental scientists are *space-time modelers* while other users at SRS would include *managers of defined objects, planners and resource managers* and even *the public at large*. Given the wide range of potential users, the functional capabilities of the EDA and the overall technical considerations should be of interest to a diverse audience.

General Considerations

The design of a complex computer system that would handle all of the functional requirements for this project required a careful evaluation of the current state of GIS implementation. Essentially, the system required simple query and display functions, two specialized data retrieval and display functions, and the ability to utilize the full capabilities of a robust GIS for modeling. In the design of the EDA, it was critical that both raster and vector GIS data models be closely linked and that conversions between them be made easily. The model selected had to also support digital elevation models as both grid and triangulated irregular networks. Finally, it was essential to be able to seamlessly integrate remote sensing and GIS data.

The ability to integrate GIS and remotely sensed data has dramatically improved over the past decade. While just a few years ago systems that simply integrated vector based GIS files with remotely sensed raster data were considered quite novel (Cowen *et al.*, 1988), they are now common functions of several commercial systems. Nevertheless, Dobson (1993) recently expressed his concerns that the growth of GIS has been hindered by limited access to and integration of remotely sensed data. In general, the design of this system followed what Dobson considered an extreme view in which remote sensing information was simply a few databases among many GIS databases.

The challenge for the design team was to determine the best way to link the GIS with the other systems and to provide a common user interface on three different platforms (i.e., Windows, Macintosh, and UNIX). In the larger context of spatial database design and implementation, the flexibility and elegance of the navigational interface affects the utility of the system to those unfamiliar with the tools (Frank, 1994). The requirement for a common user interface became the most restrictive requirement for the design of the EDA and also one of its most significant advancements. The need for the common user interface was noted by Faust *et al.* (1991, p.666) in their review of hardware and software trends:

> "The real issues in computing in the next decade involve innovations that will allow relatively unsophisticated users to access the power of the computer hardware, without having to become experts in programming and computer operating systems. The tools for GIS and remote sensing analysis should become easier to use for a novice, and at the same time be able to take advantage of the new advances in hardware and software technology."

In addition to building a common user interface, the best alternative for linking all the required functions with the GIS software had to be determined. The site selection system dictated the requirement for GIS spatial analytical capabilities; therefore, the important decision was choosing the best approach for linking these functions to the other systems. Nyerges (1992), Chou and Ding (1992), Abel *et al.* (1994), and Pascoe and Penny (1995) provide useful insights into the obstacles involved with integration of GIS and other functions. Nyerges (1992) suggests that the essential issue in the design of such integrated systems is the level of "coupling" between the various subsystems. One approach would be to use the GIS as the core of the system and develop special user interfaces for the query and retrieval functions. In this environment, the non-GIS functions would be run by launching other systems through macros that also pass the relevant data to each application. This type of system only provides a loose coupling of the various applications and would be what Abel *et al.* (1994) consider an "embedded" system. Embedding the GIS software as the core of larger system has the disadvantages of requiring the user to have a familiarity with the operation of that software and is restrictive to the GIS platform, (i.e., UNIX). These constraints dictated that the embedded GIS integration model would not satisfy the user requirements, and another approach was taken for the EDA.

Geographical Data Browsing System

Chou and Ding (1992) maintain that the level of system integration depends on the way data are shared between systems, the implementation method, and the user interface. The EDA required a high level of integration among all three of these factors. The goal was to design a system in which the GIS was tightly coupled with the other components so that they would communicate easily between each other without using GIS software as the core. Fortunately, at the start of the initial development phase, several new geographical data browsing systems were entering the market that offered an alternative design strategy. These systems provided a set of core spatial query and display functions bundled into a desktop computing environment with a standard graphical user interface (GUI). These new products, such as ArcView™ (ESRI), SPANS MAP™ (Tydac), and VistaMap™ (Intergraph), were designed to facilitate easy access to enterprise-wide spatial data. Although differing in terms of the specific interface approach, they each allow users to create their own "views" of geographical data. As discussed by Abel *et al.* (1992), these views are customized representations of existing data that are created through simple tools. Basic statistical and spatial query functions are included to facilitate selective retrieval and output of information in the form of reports, charts, and graphics. These geographical data browsing systems are increasingly being linked to enterprise wide networked databases to support planning, design, and decision-making processes (Newton *et al.*, 1992). While these products could meet some of the simple query and display requirements for the EDA, they could not, independently, meet all the needs for system integration.

The final system design decision was based on the need to use a spatial data browsing system that supported customized programming extensions for non-spatial data handling functions and provided interoperability with a robust core GIS. Based on these requirements, the EDA was implemented with ArcView™ (ESRI, 1994). The keys to this decision were the flexibility of the Avenue scripting language that was used to create a common user interface on three different operating systems, and the support of remote procedure calls to ARC/INFO (Razavi, 1995). This was a more desirable level of integration than using ARC/INFO as the core because many of the functions of the EDA did not require sophisticated GIS capabilities. As an independent desk top application, the data browsing system provides a fairly robust set of spatial data handling functions and a common user interface that is easy to customize. Using the geographical data browsing systems as the core for EDA represents a significant technological advancement. In fact, it addresses one of the weaknesses in remote sensing and GIS software identified by Ehlers *et al.* (1989, p. 1621) in that commercial systems "... lack the kind of extensibility through programming tools which are presently available, for example, with DBMS systems using fourth-generation languages." The evolution of this type of system was forecast by Frank *et al.* (1991) in their discussion of trends for the decade. In fact, they predicted that a sizable commercial market would develop to implement this type of customized integrated system for large organizations.

Database Development

In the future, we may reach a time when various GIS, remote sensing, and CAD data formats can be maintained by their owners in any format and then be directly incorporated into other systems without any transformations. In fact, very recent developments indicate that some CAD files have reached that level of integration with some GIS formats. Similarly, attribute data should be maintained in whatever spreadsheet or database management system desired and automatically linked to the relevant spatial feature. Pascoe and Penny (1995) formally describe the range of spatial and non-spatial transformations and methods of movement that data can undergo. Less formally, this project assumed a rather straightforward approach to transforming GIS and CAD graphical entities into ARC/INFO coverages. All remote sensing data were transformed into ERDAS .lan files and images were converted into TIFF format. The attribute files were converted to INFO. All of the various data elements were moved to a single UNIX workstation for initial implementation.

The data included in the EDA were collected from a wide range of sources including U.S. Geological Survey (USGS) Digital Line Graphs (DLG), aerial photography, existing USGS and U.S. Department of Energy maps, multispectral and panchromatic data, aircraft video, ASCII tables, text files, and various existing data layers from other sections at SRS. Several existing GIS layers were previously utilized in other research projects and were maintained in various systems that included ARC/INFO, ERDAS, AutoCAD, and Intergraph. The ARC/INFO coverage format was selected as the standard format, and all other data sources were converted to that data structure. While this is not the ideal way to an integrated spatial data set, it represents the only reasonable way to currently handle the problem (Abel, 1994).

Base Maps

The first step in the process was to determine an appropriate base map for the site. Sixteen USGS 7.5-minute quadrangles that contain SRS provided the most consistent and largest scale map base. Therefore, the DLG versions of these quadrangles were incorporated into the EDA to create base layers of transportation, hydrology, man-made features, and hypsography (Plate 1). In addition, the contour data were converted from a line coverage into a triangulated irregular network (TIN). The polygonal file created by the TIN was then converted to a lattice for use as the digital elevation model (DEM) in the system at a 5-metre grid cell resolution. Along with the DEM, slope and aspect coverages were created from the TIN by dissolving adjacent polygons that had similar ranges of slope or aspect. These topographic layers are important inputs in site selection and environmental modeling applications throughout SRS.

Some of the most important inputs to the EDA were closely associated with the environmental monitoring procedures at SRS. For example, the location of over 2,400 groundwater monitoring wells were included as a point coverage. Aerial gamma surveys were represented as contour lines, and defined hazardous waste units were added by converting spreadsheets with existing attribute information (Plate 2).

Remote Sensing Inputs

Remotely sensed images of SRS provide an important orientation aid for the user and were a critical input to the EDA. In order to efficiently meet the need for a visual back-drop, both SPOT 10-metre panchromatic and 20-metre multispectral images from 1989 were registered to the DLG base and were available for direct input with user designed views. The scientists also wanted to incorporate very high resolution aircraft multispectral scanner imagery into the atlas. Although it is technically feasible to rectify this type of data, the lack of uniformity among individual flight lines makes it impractical to create a mosaic of these data on a site-wide basis. Several aerial photographs of a 1973 air photo mission were scanned, enhanced, and then stored in band-interleave-by-line (BIL) format. Additional aerial photographs from a 1951 mission that were archived on CD-ROM were also rectified to the DLGs and SPOT panchromatic data. Using the roads coverage from the DLGs and a resampled 5-metre panchromatic image as reference, ground control points were recorded for the aerial photo files and registered directly with image registration in the GIS procedures. Although this was done for only a few of these photographs, it was demonstrated that historical aerial photographic missions could be an integral part of a geographical browsing system.

Initial System Configuration

After approximately six months, the initial database consisting of more than 50 layers was completed and the prototype, operating on several platforms, was demonstrated to SRS personnel. This system, without any additional enhancements, met a large proportion of the initial design considerations. Within the simple data browsing environment, it was possible to perform a wide range of display and query functions. It was possible to create user specified views from data residing on several different machines and to generate a wide variety of output.

Multi-Media Extensions

An important part of the development of the system had been the incorporation of multi-media data sources. In today's computing environment, the attributes of a geographical feature can be any form of digital data (Shepard, 1991; Shepard, 1994). For this system, it was important to integrate text, images, and full motion video. Because the data browsing software supports a wide variety of data formats, several experiments were conducted to link geographical features to these alternative data sources. For this experiment, vertical and oblique infrared videography were available for a number of facilities on the site. These data were incorporated into the system as MPEG (Motion Picture Coding Experts Group) files using analog-to-digital conversion techniques on selected frames of the videotape (Liou, 1990). These files are supported by various MPEG viewing systems that can be

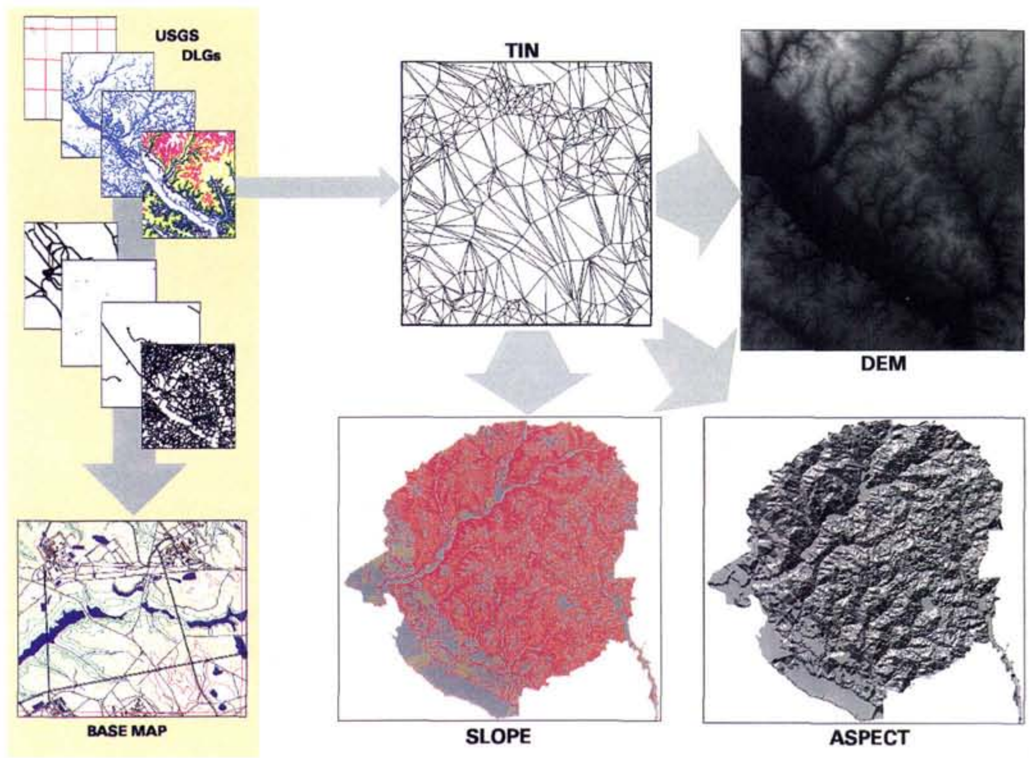

Plate 1. Creation of EDA base maps and DEM products from the USGS Digital Line Graphs.

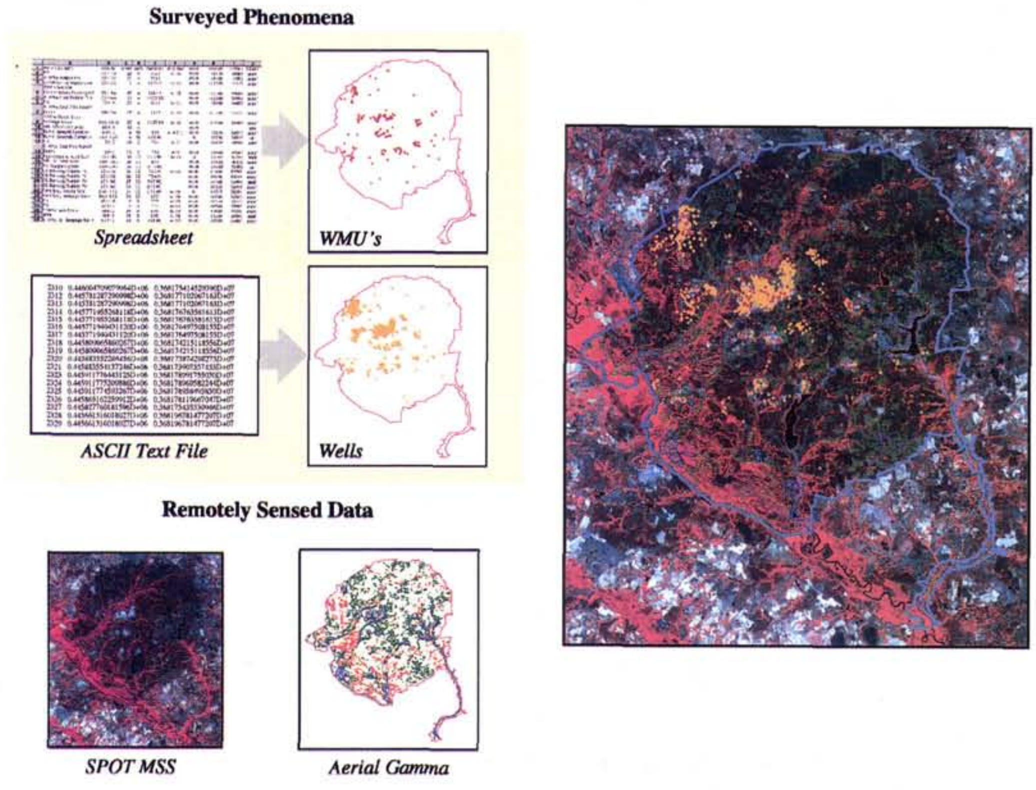

Plate 2. Significant environmental monitoring inputs to the EDA.

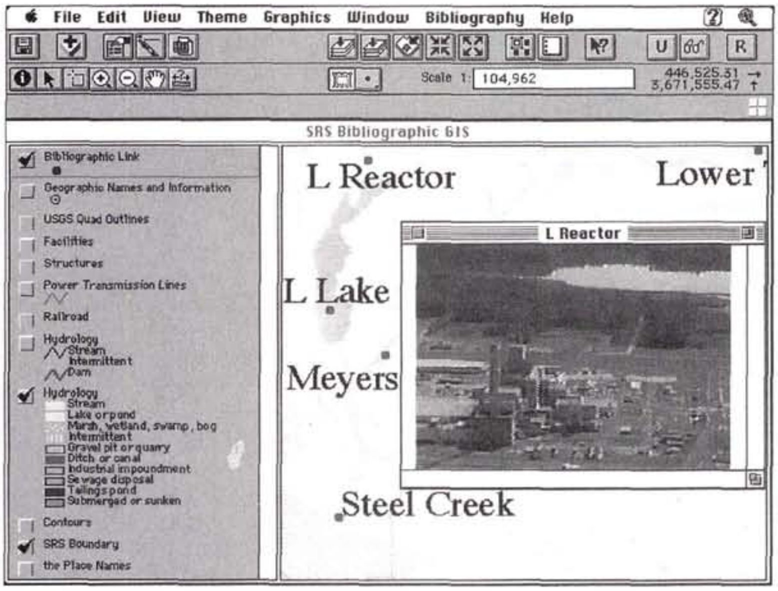

Figure 1. User interface for the EDA with an example of full motion video.

launched from the EDA (Figure 1). Although the practical scientific application of full motion video remains to be explored, the technical feasibility was achieved.

Networking Considerations

In order to maximize the potential use of the EDA, a heterogeneous client server network was required. The goal was to establish a federated environment in which the contents of the EDA could be accessed from numerous servers and displayed on any computing platform across a network. The networked environment would allow data maintenance and security to be performed at a central locale and would minimize data redundancy. The configuration of the network to support the EDA required some novel approaches. Because each platform (UNIX, DOS, and Macintosh) utilizes different native network protocols, data packet conversion elements had to be placed to optimize throughput (Figure 2). This objective was achieved by locating the protocol support interface on the server rather than the workstation. This was accomplished by using a Novell NetWare™ server as the central storage facility which supported AppleTalk, IPX, and TCP/IP interfaces. By supporting all three protocols on a Novell server, individual workstations (UNIX, DOS, and Macintosh) could be used and configured for normal operation, with the data browsing system simply being another application. This arrangement promotes a high level of interoperability in which the data are passed through the network to individual platforms in their native format (Calvo and McDonald, 1993). This approach addresses some of the problems relating to federated GIS computing environments outlined by Abel *et al.* (1994). By storing the common layers of the EDA on the server with the most restrictive DOS 8.3 naming convention, each user can easily combine these layers into customized views without physically transferring them between machines. The benefit of this approach is that layers, such as the DLG base maps, do not have to replicated on all the user workstations and may still be combined with personal data that are securely stored and maintained on individual workstations. It should be noted that if the network is sufficiently robust and the server has fast disk access, then little, if any, performance degradation may be encountered (Bresnahan *et al.*, 1994).

Another way that a user can access the EDA is through X Windows emulation on the Intel and Macintosh workstations. It should be noted that several researchers have utilized X11 Window Systems on UNIX platforms (Evans *et al.*, 1992) to establish geographical data browsing and analysis systems located on dedicated central servers (Matteson *et al.*,

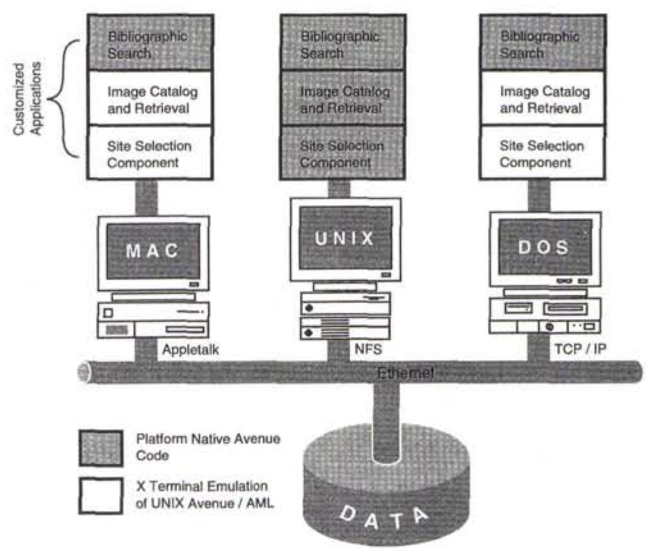

Figure 2. Multiple platform implementation scheme for the EDA.

1993; McBride *et al.*, 1993). Such systems have been designed to serve project-specific needs, and often are part of database development initiatives which would be difficult to duplicate in other locations. For the EDA, the same approach is available for users who are not interested in running the data browsing system on their own machine or need to access the site selection or photo-browsing system which only reside on the UNIX platform.

Bibliographic Search and Retrieval System

A primary objective in the design of the EDA was the creation of a method to easily determine the location and content of studies which had been conducted on the site over the course of its history. This spatially oriented bibliographic search function would enable researchers to utilize geographic location to identify and retrieve references and databases. The requirements were that a user could interactively perform a search of geographical locations within SRS to retrieve a bibliographic listing, text, images, data sets, or metadata. Similar systems are currently being developed to support geographically referenced libraries. For example, the National Center for Geographic Information and Analysis (NCGIA) Alexandria Project is one of several efforts that are aimed at defining "digital library" technology (Buttenfield, 1995). Similar to the EDA, the Alexandria project is designed to serve a very diverse set of users (Smith and Frew, 1995). Although the Alexandria Project may be more ambitious, the functions of the EDA bibliographical search system have universal applicability for any group that needs to retrieve data based on geographical location.

The bibliographic system was developed with the Avenue scripting language within ArcView. A script written in Avenue groups together the means to automate tasks, add new capabilities, and build complete applications (ESRI, 1994). A key component of the system is that all documents are dynamically linked so that changes made to the data are automatically updated in each document in which it is used. The scripting capability can be used to customize user interfaces by linking complex actions to a particular menu button. In addition, communication between the browsing system and other applications or programs can be created with the scripting tools. The key to the creation of the bibliographic system was a geographic "hot link" which is a hyper-media function that attaches geographic features of a theme to various kinds of data and software objects based on a query or initiated by a request (Andrews and Tilton, 1993).

In a hyper-media computing environment, "hot links" enable the dynamic display of additional data such as text files, images, digital video, or documents. To link to external data, geographical features are selected using a unique graphic cursor. Then, in an interactive environment, the system performs the specified action by using the value from an individual field of the theme's attribute table. "Hot links" within individual themes invoke discrete actions on a theme-by-theme basis.

The set of geographical features for SRS was created from the U.S. Geological Survey Geographical Names Information System (GNIS) and other official USGS and Department of Energy maps. In order for this system to work, two different "hot linking" actions were linked to these named features. One action was required to retrieve the bibliographic data and another to retrieve images. Shepherd (1991) suggests that the "simplest" approach for associating spatial features with images is to link the image to a "point-located" feature. For the scope of this project, the decision was made to follow the same logic and use a point coverage as the lowest common denominator for the location of all "hot linked" features. This meant that linear and polygonal features such as streams and lakes were only represented by a single label point. Although related features are represented by discrete elements, spatial selection tools can be used to define search criteria. These include capabilities to retrieve points based on radial searches, bounding rectangles, or buffers along line segments. Using pan, zoom, selection, and measuring tools, a user can easily navigate around SRS and find multiple features within specified distances of points of interest.

In addition to the design of the computing environment for selection of features, a major concern was populating the text and image-based bibliographical data sets. One approach involved paper documents and a considerable amount of manual editing while a second method utilized digital data and an extensive set of programs to create the required databases. In the first stage, the bibliographic data consisted of several hundred articles written by SRS scientists. Each article was assigned to a geographic location on the site. From that point, the first page of each article was scanned and optical character recognition (OCR) was performed. Images found in the articles were scanned and saved as individual files in TIFF format and given names associated with the SRS publication numbering system.

A second round of bibliographic data acquisition was based on the SRS Ecology Environmental Information Document on CD-ROM (Wilke *et al.*, 1993). The entire document consisted of 21 chapters, each containing a "references" section and an overall bibliography listing all references. The chapters and the individual alphabetical listings were separate files. The text of the chapters was combined sequentially into one document. The associated references were put into individual chapter reference files. To create the final master bibliography, the two sets of data (chapter references and overall bibliography) were merged and sorted. A frequency count was built based on the author-date pair. The file was then presented to an "expert" editor who determined which references were to be retained. Once this was edited, a comprehensive set of references was directly linked to any geographical keyword that appeared in the same paragraph with the citation. Although this procedure does not assure that the reference is specifically related to the geographic feature, it suggests to the user that some aspect of the citation is associated with that part of the site.

In order to operate the system, users may design their own customized view of relevant layers. For example, a biologist may create a view based on land cover, soils, and vegetation classes while a hydrologist may be more concerned with digital elevation models and hydrological features. In order to access the data, the user must include the "hot link" point coverages for bibliographical and image based data. By selecting ("hot linking") a point, bibliographic entries and scanned images pertaining to that location are retrieved and displayed (Figure 3). Therefore, although there is a generic look and feel to the system, users design their own view from which the bibliographic system is activated.

Additional functions were added that enable users to update the bibliographic database by filling out a form and adding a new named feature. By recording the location of the cursor while using the data browsing system, the coordinates of discrete locations are easily defined by users. In its final

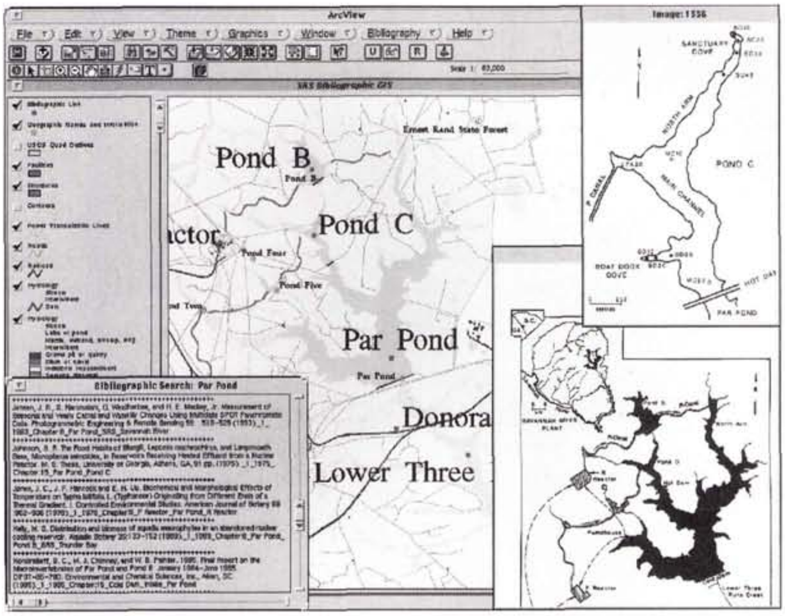

Figure 3. Bibliographical search system for the EDA demonstrating both text and image retrieval.

form, the bibliographic system met all the functional requirements and operated on as a stand alone application supported by three different operating systems.

Image Browse and Retrieval System

The Image Browse and Retrieval System was developed to provide an efficient way to search for and display any combination of approximately 80,000 aerial photographs and hundreds of satellite images obtained over SRS during the past 50 years. It is a seamless, integral component of the EDA with a specially designed graphical user interface (Plate 3). It was developed using communication between Avenue and the ARC Macro Language (AML) programming languages. Novice users can conduct tabular or geographic searches of the database to identify the availability of all types of remote sensor data. They initially browse a low spatial resolution version of the imagery that is registered to a base map of the site. They may then view the archived high spatial resolution version of the imagery if desired (Gladney, 1993). A user may also download a digital copy of the archived imagery to their workstation.

Tabular Searches

The image browse and retrieval system was designed to be used by persons with limited knowledge of remote sensing or GIS. The simplest search method is a tabular search where the user identifies (1) the season(s) of interest, (2) the type(s) of imagery desired, and (3) the year(s) of interest. These criteria are then used to perform a search of the tabular data associated with each of the images in the database. Images that meet the selection criteria are displayed as wire frame boxes (Foote, 1987), and/or as "postage stamp" browse quality images overlaid on the SRS digital base map. For example, Plate 3 displays a flight line of eight overlapping stereoscopic panchromatic aerial photographs acquired in the spring of 1974 overlaid onto the base map. For illustration purposes, a portion of a SPOT panchromatic image in browse file format is also depicted. The user may then click on an individual frame to request that the archived high spatial resolution image be brought to the screen. The tabular database also contains detailed information about the date of imagery, altitude above ground level at the instant of exposure, camera focal length, film type, filter, UTM coordinates of the four corner coordinates, and scale.

Hypertext and Spatial Searches

Geographic searches may be performed using either hypertext or spatial queries. For example, a user may search the remote sensor data coverage for very specific geographic sites such as numerous environmental studies that have been performed on Par Pond or Pen Branch. These high priority study areas have color hypertext names on the base map similar to the bibliographic system. The user simply clicks on these names and then answers questions about image type, season, and year to more carefully guide the search. The traditional search method allows the user to click and drag the mouse over a geographic region of interest on the basemap. The user then initiates a search within this geographic area by image type, season, and year.

Important Issues

There are a number of important issues that must be resolved when developing an image browse and retrieval system. First, a decision must be made about the spatial resolution of the browse image data versus the archive image data. Table 1 summarizes the relationship between input image scale, digitizer detector IFOV measured in dots per inch (DPI) and micrometres, and output image spatial resolution in metres. In the current version, browse images are scanned at 100 DPI (254 μm) whereas archive images are stored at 2,000 DPI (12.7 μm). For vertical aerial photography obtained at 1:20,000 scale, this translates to browse images with a spatial resolution of 5.08 by 5.08 m and an archive spatial resolution of 0.25 by 0.25 m (less than 1 ft by 1 ft) (Jensen, 1996).

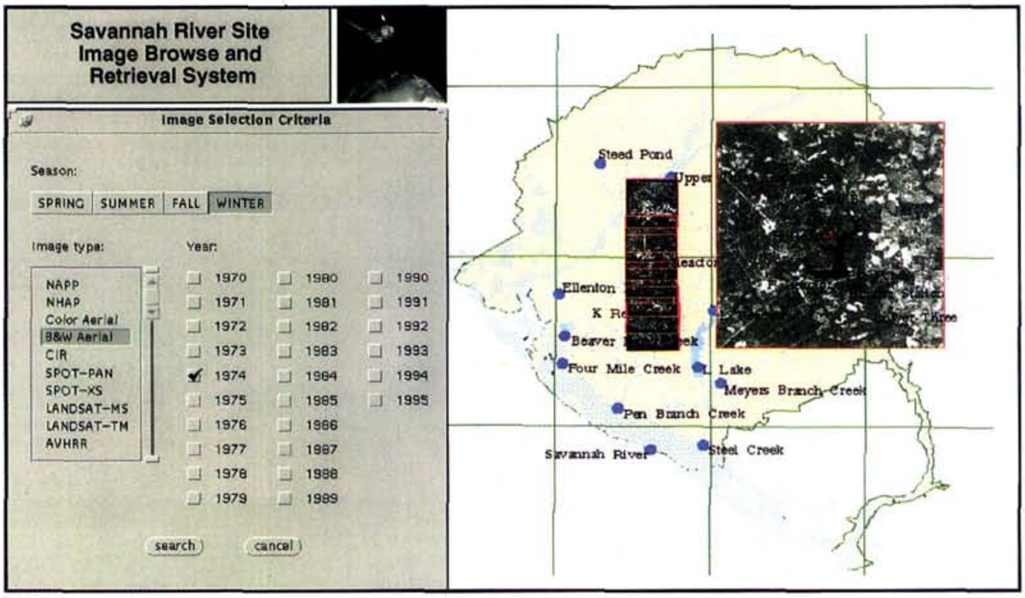

Plate 3. Image browse and retrieval system for the EDA demonstrating selection criteria.

Table 1. Relationship between Digitizer Instantaneous-Field-of-View (IFOV) Measured in Dots-per-inch or Micrometres and the Pixel Ground Resolution at Various Scales of Photography

Digitizer Detector IFOV		Pixel Ground Resolution at Various Scales of Photography (metres)					
Dots per inch	Micrometres	1:40,000	1:20,000	1:9,600	1:4,800	1:2,400	1:1,200
100	254.00	10.16	5.08	2.44	1.22	0.61	0.30
200	127.00	5.08	2.54	1.22	0.61	0.30	0.15
300	84.67	3.39	1.69	0.81	0.41	0.20	0.10
400	63.50	2.54	1.27	0.61	0.30	0.15	0.08
500	50.80	2.03	1.02	0.49	0.24	0.12	0.06
600	42.34	1.69	0.85	0.41	0.20	0.10	0.05
700	36.29	1.45	0.73	0.35	0.17	0.09	0.04
800	31.75	1.27	0.64	0.30	0.15	0.08	0.04
900	28.23	1.13	0.56	0.27	0.14	0.07	0.03
1000	25.40	1.02	0.51	0.24	0.12	0.06	0.03
1200	21.17	0.85	0.42	0.20	0.10	0.05	0.03
1500	16.94	0.67	0.34	0.16	0.08	0.04	0.02
2000	12.70	0.51	0.25	0.12	0.06	0.03	0.02
3000	8.47	0.33	0.17	0.08	0.04	0.02	0.01
4000	6.35	0.25	0.13	0.06	0.03	0.02	0.008

Scanning Conversions

DPI = dots per inch; μm = micrometres; I = inches; M = metres

From DPI to Micrometres:	μm = (2.54/DPI) 10,000
From Micrometres to DPI:	DPI = (2.54/μm) 10,000
From Inches to Metres:	M = I × 0.0254
From Metres to Inches:	I = M × 39.37

Computation of Pixel Ground Resolution:

PM = pixel size in metres; PF = pixel size in feet; S = photo scale

Using DPI:	PM = (S/DPI)/39.37	PF = (S/DPI)/12
Using Micrometres:	PM = (S × μm) 0.000001	PF = (S × μm) 0.00000328

For example, if a 1:6,000-scale aerial photograph is scanned at 500 DPI, the pixel size will be (6,000/500)/39.37 = 0.3048 metres per pixel or (6,000/500)/12 = 1.00 foot per pixel. If a 1:9,600-scale aerial photograph is scanned at 50.8 μm, the pixel size will be (9,600 × 50.8) (0.000001) = 0.49 m or (9,600 × 50.8) (0.00000328) = 1.6 feet per pixel.

Many of the negatives and diapositives from the years 1930-1980 are decomposing rapidly and must be archived if their information content is to be preserved. For this reason, the scanning hardware and software must maximize resolution and minimize storage requirements while expeditiously recording data.

With over 80,000 aerial photographs to archive at two spatial resolutions (browse and archive), data storage becomes a serious problem. It is possible to utilize various loss-less image compression algorithms to dramatically decrease the image storage requirements (Russ, 1992; Jensen, in press). However, the most suitable lossy and/or loss-less image compression algorithm(s) have not been determined as yet (e.g., JPEG, fractal, wavelet, run-length encoding). In addition to the compression routine to be used, it is important to consider the best medium (e.g., magneto-optical disk, tape) for long term archival storage of huge amounts of image data. It must have longevity, be inexpensive per gigabyte, and be quickly accessible (Rothenberg, 1995).

Image rectification is also an important issue. To use remote sensing imagery in the EDA, it is necessary to perform at least a cursory rectification of the image data so that it is registered in its proper location on the base map. Currently, each of the individual frames of imagery are rectified using first-order image rectification and approximately six ground control points per photograph. It is not clear whether the browse and archive image files should be rigorously rectified so that subsequent quality rectification is not necessary, or be rectified in a cursory manner sufficient for image browsing. This decision has obvious significant cost implications.

Site Selection Model

The final section of this paper describes the way the EDA is evolving into a management tool. Recently, SRS and other Department of Energy facilities have been presented with the task of siting a wide variety of new activities within their boundaries. These include landfills, waste disposal sites, and power facilities. Furthermore, the immediate goals of the environmental monitoring program at SRS are to identify and quantify the effects of site activities on the environment. Although GIS and remote sensing approaches have been used in previous DOE site planning investigations (WSRC, 1992a; WSRC, 1992b; Siderelis, 1992; Jensen, 1986), access to these analysis tools is still limited to a small group of trained users. Therefore, it was important to incorporate multi-factor suitability modeling tools into the EDA. In other words, the data browsing system needed to evolve into an operational spatial decision support system (SDSS) (Densham, 1992). The essence of a SDSS is that it couples the spatial data handling functions of a GIS with the power of a spatial modeling system to "facilitate deep thinking about a relatively complex problem (Nyerges, 1992)." The linkage between GIS and environmental models has been reviewed by Kemp (1992) and Ferda (1993) and remains a major challenge for GIS system designers. As Nyerges (1992, p. 538) states, "If indeed a GIS (data-based that is) is different than SDSS, then should a spatial analytical model coupled to a GIS be called a SDSS, a GIS or a mess?"

The primary mission for the SDSS at SRS is to support site selection activities. These site selection processes involve the implementation of several exclusionary criteria that eliminate certain types of geographic features based on environmental regulations or mandates. Examples of these exclusionary criteria include the location of wetlands, 100-year flood plain, and sensitive areas such as threatened and endangered species. The potential sites are then ranked and weighted to determine a score based on their suitability. A site's individual score or rating is calculated by summing criteria ratings (Tomlin and Johnson, 1993).

The challenge in the design of the site selection system was to incorporate sophisticated GIS modeling functions into the data browsing computing environment. As Chou and Ding (1992) suggested, instead of requiring a low-level exchange of data between an externally generated model and a GIS, it is desirable to actually construct the modeling system to operate within the GIS. To accomplish this goal, a close coupling of two different software systems is required. For this implementation, it was highly desirable to "hide" the GIS component from the user. The design required a careful analysis of the appropriate spatial data models and interoperability between different hardware platforms. In a simple data browsing environment, both raster and vector data can be visualized. However, a site selection system requires true spatial overlay and buffer functions that must be performed in a single data model. Because overlay and buffer operations are performed much quicker in raster-based GIS as compared to their vector counterparts, raster analysis was used in the site selection component of the EDA.

The design of the user interface and site selection model was implemented by customizing Avenue scripts that launch ARC/INFO functions and menus through remote procedure calls (Figure 4). This approach enables the user to access the site selection system from the EDA interface by clicking on a "button." The remote procedure call transfers control to ARC/INFO and presents the user with a custom interface. This main user interface consists of a series of pull-down menus, "widgets" (interactive graphical objects), and map- and text-based displays which help to determine a site's overall suitability score. The first step in the modeling process is to set the resolution of the cell based on the desired processing speed and spatial accuracy. Locational criteria are then selected by checking theme widgets on or off, and applying ranks and weights for each theme. The site selection model is then run within GRID using raster-based buffer, overlay, and weighting functions that evaluate the criteria. Other check lists enable the user to display any of the data layers used in the analysis, including the final sites. The current settings of the model may then be saved to an ASCII file for future modifications or processing.

Once the user exits the site selection system, the EDA is re-opened with the selected sites being added to the view. In this manner, the sites can be treated as any other theme and included in map displays, charts, or reports. An important part of the coupling of the two software environments is the conversion between data structures. Although the site selection models are performed with grid models, the data browsing system deals better with vector based themes. In fact, grid models are treated the same as images in the EDA and cannot be queried or selected. Therefore, before the selected zones are returned to the EDA, they are converted from the grid-cell format into a vector polygon format. This enables the results to be added to an existing project as a new theme that is totally compatible with the EDA. The graphical user interface of the data browsing system enables the analytical processing within ARC/INFO to remain transparent to the user. Furthermore, all resultant coverages can reside in their original file location without modification. This level of transparency is an important aspect of a Spatial Decision Support Systems (Densham, 1992). It should be noted that, presently, this high level of system transpar-

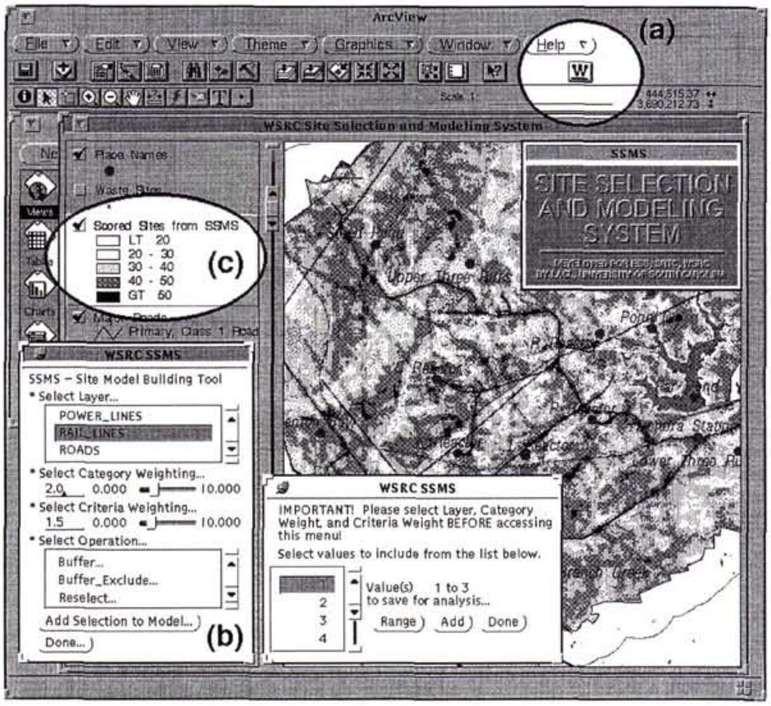

Figure 4. Site selection and modeling system for the EDA. (a) Customized button that calls GIS software. (b) Menu for selecting inputs. (c) Results of model added to EDA interface.

ency is restricted to the UNIX platform where ARC/INFO must run.

Conclusions

The Environmental Data Atlas described in this paper was developed over a three-year period. During that time, the core software also evolved to incorporate important capabilities to customize applications and interfaces and to support inter-application linkages to full featured GIS. As a result, the capabilities of the final system exceeded the initial objectives. The current EDA supports many forms of spatial data, including remotely sensed imagery, scanned maps, and aerial photographs. It can also incorporate a full range of multi-media ancillary data, including full motion video. The system is accessible from several different computing environments that support UNIX, Windows, and Macintosh operating systems. It is established as a full client-server network application in which users may combine spatial data on local hard drives with data from centrally maintained repositories. From these customized views, users can launch subsystems that enable them to retrieve bibliographical records and to browse aerial photograph archives. Initial steps have also been made to integrate complex analytical functions into the system.

It is important to assess how the features of this system fit into the evolution of GIS and remote sensing systems. In 1989, Ehlers *et al.* discussed the necessary evolution of these two important spatial data handling tools. At that time commercial systems that simultaneously displayed raster images and vector GIS files were just emerging. Although the ideal totally integrated system that they described still does not exist on the commercial marketplace, there has been significant progress in the integration of these systems over the first half of this decade. From Ehlers viewpoint, the important technological advancement represented by the EDA is the ability to extend the spatial tools with general programming tools. From the hardware perspective outlined by Faust *et al.* in 1991, the most significant factor has been the capability to perform many of these spatial data handling tasks on common business computers under standard operating systems. In fact, there is negligible performance differences for many of the standard data browsing functions of the EDA running on either the Windows based version running on a 90 MHz Pentium processor or a UNIX workstation. Furthermore, the scripts written in the fourth generation language to perform the bibliographic search were easily migrated between the UNIX and the Windows and Macintosh based platforms.

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