UTILIZING GEOGRAPHIC INFORMATION SYSTEMS TECHNOLOGY IN THE WYOMING CUMULATIVE HYDROLOGIC IMPACT ASSESSMENT MODELING PROCESS[1]

by

Jeffrey D. Hamerlinck and James R. Oakleaf[2]

Abstract: The coal-permitting process places heavy demands on both permit applicants and regulatory authorities with respect to the management and analysis of hydrologic data. Currently, this correlation is being addressed for the Powder River Basin, Wyoming by the ongoing Cumulative Hydrologic Impact Assessment (CHIA) efforts at the University of Wyoming. One critical component of the CHIA is the use of a Geographic Information System (GIS) for support, management, manipulation, pre-analysis, and display of data associated with the chosen groundwater and surface water models. This paper will discuss the methodology in using of GIS technology as an integrated tool with the MODFLOW and HEC-1 hydrologic models. Pre-existing GIS links associated with these two models served as a foundation for this effort. However, due to established standards and site specific factors, substantial modifications were performed on existing tools to obtain adequate results. The groundwater-modeling effort required the use of a refined grid in which cell sizes varied based on the relative locations of ongoing mining activities. Surface water modeling was performed in a semi-arid region with very limited topographic relief and predominantly ephemeral stream channels. These were substantial issues that presented challenges for effective GIS/model integration.

Additional Key Words: coal mine reclamation, Powder River Basin, ARC/INFO GIS, MODFLOW, HEC-1.

Introduction

The coal-permitting process places heavy demands on both permit applicants and regulatory authorities with respect to the management and analysis of hydrologic data. Currently, this correlation is being addressed for the Powder River Basin, Wyoming by the ongoing efforts to develop a Cumulative Hydrologic Impact Assessment (CHIA) at the University of Wyoming. One critical component of the CHIA is the use of a Geographic Information System (GIS) for support, management, manipulation, pre-analysis, and display of data associated with the chosen groundwater and surface-water models. This paper will discuss the methodology in using of GIS technology in the CHIA modeling process.

Background

Cumulative Hydrologic Impact Assessment

Surface coal-mining activities result in modifications to the natural landscape that have or will potentially impact surface and groundwater resources. Through employment of proper reclamation techniques, the hydrologic impacts of individual surface coal-mining operations can be significantly minimized. However, postmining or residual impacts, though individually insignificant, may, with development of additional mines, accumulate to magnitudes that are potentially damaging to the hydrologic balance of the area (OSM, 1985).

The requirements for obtaining a permit to conduct coal mining under the federal Surface Mining Control and Reclamation Act of 1977 (SMCRA) contain provisions for mitigating adverse cumulative impacts, focusing on the collection, analysis, interpretation and application of "baseline" hydrologic information. Specifically, permitting requirements call for the development of hydrologic predictions by both the applicant and the regulatory authority, in order to provide a means by which: 1) water resources are characterized; 2) potential impacts are identified; 3) appropriate mitigation or prevention of those impacts is achieved; and 4) verification of results is obtained, thus ensuring that

---

[1] Paper presented at the 1997 National Meeting of the American Society for Surface Mining and Reclamation, Austin, Texas, May 10-15, 1997.

[2] Jeffrey D. Hamerlinck, GIS Coordinator and Associate Research Scientist; James R. Oakleaf, Assistant Research Scientist, WY Water Resources Center, Univ. of Wyoming, Laramie, WY 82071

Proceedings America Society of Mining and Reclamation, 1997 pp 667-678
DOI: 10.21000/JASMR97010667

https://doi.org/10.21000/JASMR98010667

mine sites are reclaimed as productive postmining areas (OSM, 1991).

In conjunction with the permit applicant's Probable Hydrologic Consequences (PHC) determination, regulatory authorities are required, before issuing a permit to conduct surface coal mining and reclamation, to complete a CHIA of all anticipated mining in the area to assure that the proposed operation has been designed to prevent material damage to the hydrologic balance outside the permit area (OSM, 1985).

The CHIA process involves completion of six major steps: 1) define the area to be studied, known as the cumulative impact area or CIA; 2) describe the hydrologic system and determine baseline hydrologic-resource values; 3) identify hydrologic resources likely to be affected; 4) develop standards for determining impacts; 5) estimate the impacts of mining on the hydrologic resources; and 6) make a material damage determination and prepare a statement of findings (OSM, 1985). In Wyoming, SMCRA provisions for a surface-mining permit and associated CHIA requirements are promulgated under the Wyoming Environmental Quality Act. As a primacy state, this regulatory authority is administered by the Department of Environmental Quality, Land Quality Division (DEQ/LQD).

The Wyoming Initiative

"The hydrology provision for permitting has been among the least understood requirements under SMCRA... Because the hydrologic issues which arise are tied to the environment in which the operation is to be permitted, and because there are differing types of operations and differing environments each with its own set of potential impacts, it is impossible to develop a standard methodology which would satisfy all possible situations," (OSM, 1991, p. 1).

A comprehensive understanding of regulatory requirements specific to CHIA has been hampered in part by difficulties encountered in transferring and adapting successful methodologies between permit environments (OSM, 1991). The results of the last basin-wide CHIA carried out for Wyoming's Powder River Coal Region identified a need to establish coordinated and efficient methods for collecting, storing, accessing, manipulating and analyzing data required for carrying out future hydrologic impact assessments (Martin, et. al., 1988).

In 1992, in partial response to the data management needs identified above, the Office of Surface Mining (OSM) launched the Wyoming Initiative, a program focusing on three major arenas within the coal-mine permitting and reclamation process.[3] These arenas include: 1) development of a revised, dynamic CHIA process; 2) electronic permitting facilitation; and 3) transfer of OSM's Technical Information Processing System capabilities to regulatory authorities and permitees through a comprehensive training program. Critical to each of these efforts is the need for establishing a framework for hydrologic data exchange, access and sharing, and associated scientific applications related to Wyoming's surface and groundwater resources in the context of surface mining activities across the state.

GIS, Hydrology and Mine Land Reclamation

GIS and Hydrologic Modeling. The use of computers in hydrologic analysis has become increasingly widespread among hydrologists and modelers alike. Because hydrology is linked in so many ways to processes at the earth's surface, the connection to such sophisticated computer-based technologies as geographic information systems (GIS) is a predictable step in the evolution of hydrologic analysis (De Vantier, et. al., 1993).

Simply defined GIS is a computer-based information technology which stores, analyzes, and displays both spatial and non-spatial data (Parker, 1988; Maguire, 1991). In the last 20 years, GIS technology has been increasingly applied to a wide range of water-resource-related studies (Males and Grayman, 1992). Specifically, "..hydrologic applications of GIS have ranged from synthesis and characterization of hydrologic tendencies to prediction of response to hydrologic events, " (DeVantier, et. al., pg. 247).

Maidment (1993) provides the following interpretation of the relationship between GIS technology and hydrologic modeling:

> GIS provides representations of the spatial features of the Earth, while hydrologic modeling is concerned with the flow of water and its constituents over the land surface and in the subsurface environment... Hydrologic modeling has been successful in

---

[3] - The Wyoming Initiative was established through a state/federal interagency cooperative agreement involving the USDI Office of Surface Mining and Bureau of Land Management, the Wyoming Department of Environmental Quality, the Wyoming State Engineer's Office, the Wyoming State Geological Survey, and the University of Wyoming (Cooperative Agreement No. DOI-OSM-BLM; WY DEQ; WY SEO; UW-93-1, 1993).

> dealing with time variation, ...but spatial disaggregation of ...study area[s} has [traditionally] been relatively simple. In many cases, hydrologic models assume uniform spatial properties or allow for small numbers of spatial subunits within which properties are uniform. GIS offers the potential to increase the degree of definition of spatial subunits, in number and in descriptive detail... (Maidment, 1993, page 147).

GIS-hydrologic-model integration may be grouped into four major categories: 1) hydrologic assessment; 2) hydrologic parameter determination; 3) hydrologic modeling inside GIS and linking GIS; and 4) hydrologic models. Of these categories, hydrologic parameter determination and GIS-hydrologic model linking are currently the primary focus of ongoing research nationwide (Maidment, 1993). Relative to GIS-modeling linking, numerous example may be identified in the current literature which illustrate the development of applications linking GIS to both surface-water (Yoon, et.al., 1993; Sasowsky, et. al., 1991) and groundwater hydrology models (Hinaman, 1993; El-Kadi, et.al., 1994).

The advantage of integrating GIS into the hydrologic modeling process, is in its ability to relate different data sets through the common denominator of location. GIS links data sets and analyzes them as a unit within one integrated system, making it an excellent tool for managing the modeling process, analyzing the results, and updating and archiving spatially-referenced data sets (Richards, et. al., 1993).

GIS and Mine Reclamation. The use of GIS in the management of mining activities and mine reclamation is a new and growing application of the technology. Specific examples of recent work related to coal mine reclamation include development of GIS-based statistical methods for conducting coal availability studies (Watson and Bryant, 1993), spatial predictive modeling of mine subsidence risk (Hao and Chugh, 1993), and restoration of polluted streams and watersheds stemming from acid mine drainage associated with abandoned coal mines (USEPA and OSM, 1996). GIS has also been incorporated into the Office of Surface Mining's Technical Information Processing System (OSM, 1991), which is utilized in many state Regulatory Authority offices for tracking permit compliance, etc.

GIS and Wyoming's CHIA Modeling Process. A logical merging of technologic applications can be realized when incorporating GIS into the cumulative hydrologic impact assessment process. This paper outlines the utilization of GIS in the modeling process developed for conducting CHIAs in the Powder River Basin of northeastern Wyoming. The following sections focus on the methods applied in the use of GIS to develop, manipulate, and display model inputs and outputs.

Methods

The GIS utilized in this study was ARC/INFO® GIS, a relational, arc-node vector/raster-based system running in a UNIX® operating system environment. Application development was carried out using ARC/INFO's Arc Macro Language (AML). This language is an interpreted language modeled after Prime Computer, Inc.'s Command Procedure Language (CPL) and provides programming capabilities and a set of tools for tailoring the user interface of ARC/INFO applications. These specific products were selected based on compatibility with other cooperating parties and pre-existing expertise with the software.[4]

Surface water modeling was performed using HEC-1 and generally required data layer overlays and querying of the GIS database. HEC-1 is a lumped parameter, rainfall-runoff and flood-prediction model developed by the United Sates Army Corps of Engineers (Peacock, et. al., 1996). Groundwater modeling employed the United States Geological Survey's Modular Three Dimensional Finite Difference Groundwater Flow Model (MODFLOW; McDonald and Harbaugh, 1988) and directly used manipulated GIS data layers as inputs in the modeling process.

Study Area and Needs Assessment

All hydrologic models require the input of data, and, regardless of what is being modeled, there are certain factors that must be considered before gathering these data. First, the study area must be defined; subsequently needs specific to the models are assessed. Once these items have been addressed, development of the data can begin.

Study Area. Due to modeling efforts being directed towards both groundwater and surface

---

[4] The remainder of the text will make reference to ARC/INFO GIS specific commands and functions in *ITALIC CAPS*.

water, two separate CIA study areas were developed for the Little Thunder Creek CHIA. The study area boundaries related to the hydrologic regimes for surface water (defined by Little Thunder Creek watershed), and groundwater (defined by geological lineaments, faults, and folds). Three coal mines (Jacob's Ranch, Black Thunder, and North Rochelle) located within the study area were the focus of modeling efforts.

For the surface-water modeling, the 250 mi^2 watershed of Little Thunder Creek established the study area in question. This watershed is located in Southeast corner of Campbell County and is a tributary of the Cheyenne River Drainage Basin (Figure 1). On the groundwater modeling side, a grid centered over the three mines (angled north-northwest) constituted the two-dimensional spatial extent of the study area (Figure 1). This grid covered 790 mi^2 and encompasses not only the three mines, but also a portion of the coalbed methane wells found in the region and four additional coal mines (Peacock et al., 1996).

Needs Assessment. Once the study areas had been defined, it was necessary to determine what spatially- referenced data were required. Through careful collaboration among modelers and GIS analysts involved with the pilot CHIA process, 18 GIS data layers were initially identified for development. These layers could be classified by feature type (point, line, or polygon), spatial application (groundwater aquifer system or surface hydrology watershed, or both), and functionality (modeling or cartographic reference). Table 1 provides a brief outline of the type of data layers developed, the feature type, the spatial extent, and the use of each.

GIS Development

Once the study areas had been defined and the initial data requirements established, the next objective was to develop the GIS layers. Five steps were identified for the development and manipulation of each GIS data layer required in the modeling process: 1) data acquisition; 2) data automation; 3) database design and construction; 4) quality control; and 5) metadata. For the CHIA pilot study, data acquisition required the most time, followed closely by database design and construction (Figure 2).

Data Acquisition. Data for the CHIA could be classified as digital or analog and was provided by an assortment of state and federal agencies in a variety of scales and formats. Some of the more common forms, other than Arc/Info, were paper and

Table 1: GIS data layers for pilot CHIA.

Data Layer	Feature Type	Spatial Extent	Use
Surface Water Flow Stations	point	surface water	modeling
Climate Stations	point	surface water	modeling
Surficial Hydrography	line/polygon	surface water	modeling
Vegetation	polygon	surface water	modeling
Soils	polygon	surface water	modeling
Surficial Geology	polygon	surface water	modeling
Bedrock Geology	polygon	both	modeling
Coal Faults and Folds	line	groundwater	modeling
Coal Isopach	point/polygon	groundwater	modeling
Coal Burnline	line	groundwater	modeling
Clinker	polygon	both	modeling
Monitoring Wells	point	groundwater	modeling
Mining Sequence	polygon	both	modeling
Surface Water Rights	polygon/point	surface water	modeling
Ground Water Rights	point	groundwater	modeling
Digital Elevation Models	point/polygon	both	modeling
Public Land Survey System	polygon	both	cartographic
Transportation	line	both	cartographic

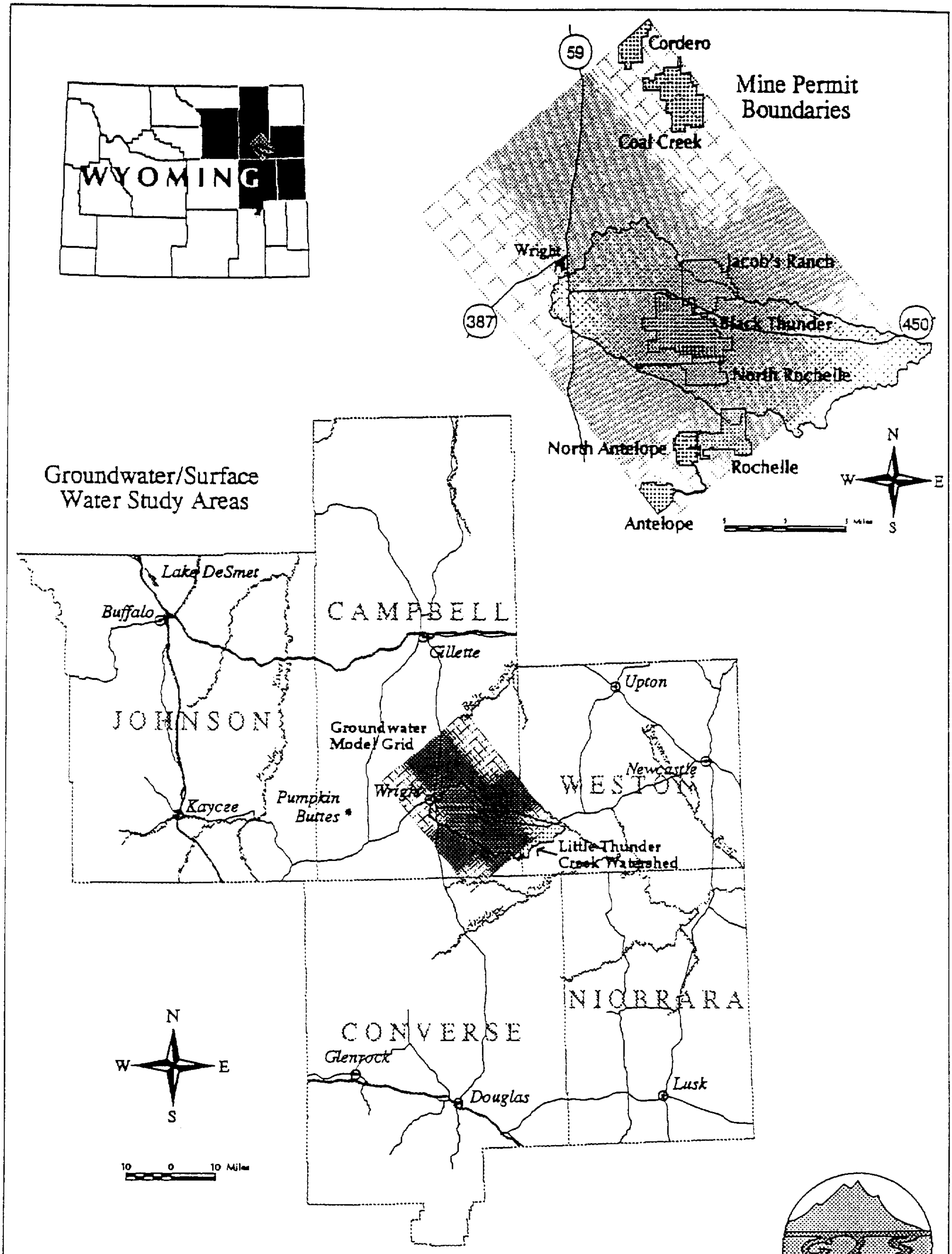

Figure 1: Location of Pilot Study Area

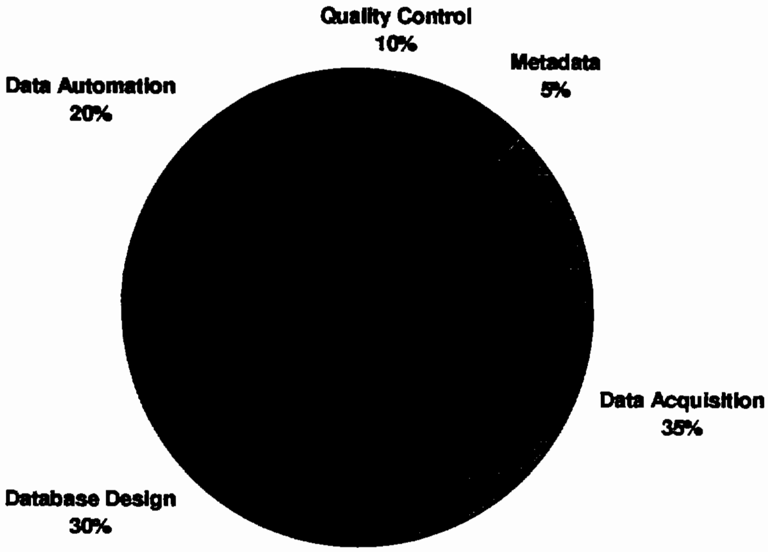

Figure 2. GIS data layer development, percentage of time required per step.

mylar maps, AutoCad data exchange files, and database and ASCII files. Additionally, some mining operations provided large scale, mine-specific data that were also incorporated into the modeling process.

Data Layer Automation and Management. This is the process of converting data from its existing source format to a digital, spatially-referenced GIS layer while maintaining each data layer in the same projection and units. Different techniques were employed to create the 18 GIS data layers and depended directly on the original format of the data. Hardcopy maps were either digitized or scanned. AutoCad files and dBase tables were directly converted into ARC/INFO through the *DXFARC* and *DBASEINFO* commands respectively. ASCII text files were manipulated and formatted by AWK (UNIX based pattern scanning and processing language) scripts allowing for the *GENERATE* command to be applied. These techniques were the most common methods of data automation throughout the pilot study. Many additional steps accompany these commands and by no means were these the only methods applied; however, such a detailed discussion of data automation is beyond the scope of this paper. Table 2 list these data layers displaying the scale, the source, and briefly explains the conversion technique employed for each layer.

Once data are converted into their respective GIS data layers, the layers must be projected into a common coordinate system allowing for data compatibility in the modeling process. For the CHIA pilot study, all the data layers were projected to a state plane coordinate system in reference to the Wyoming, East Zone. This coordinate system uses a Lambert projection and measures units in feet, consistent with the units employed in the surface and groundwater models (inches, feet, cfs, acre-feet, etc.).

Database Design and Construction. Creating a sound structure in which modelers can access and use the data layers becomes essential even with only 18 layers. First, the layers were divided by application-dependent areal extent for groundwater and surface water. Then each layer was placed under a thematic directory. For example, both monitoring and agricultural/stock wells were placed under a wells subdirectory of the groundwater directory. This allows for a logical and systematic approach to organizing the data.

In addition to the overall data structure, each individual data layer could have numerous attribute fields associated with each depicted

Table 2: GIS data layers' scale, source, & automation method .

Data Layer	Scale	Source	Conversion Technique.
Surface Water Flow Stations	n/a	WWRC	DBASEINFO
Climate Stations	n/a	WWRC	DBASEINFO
Surficial Hydrography	1:24,000	7.5 minute USGS quadrangles	digitizing
Vegetation	1:100,000	Wyoming GAP Analysis Project	pre-existing
Soils	1:250,000	NRCS	pre-existing
Surficial Geology	1:100,000	WWRC	pre-existing
Bedrock Geology	1:500,000	WWRC	pre-existing
Coal Faults and Folds	1:62,500	USGS (Denson, 1980)	digitizing
Coal Isopach	n/a	Wyoming DEQ/LQD Coal Permit and Reclamation Database	ASCII to Arc/Info with GENERATE
Coal Burnline	1:24,000	BLM (Heffern, 1996)	digitizing
Clinker	1:24,000	BLM (Heffern, 1996)	digitizing
Monitoring Wells	n/a	Wyoming DEQ/LQD Coal Permit and Reclamation Database	ASCII to Arc/Info with GENERATE
Mining Sequence	1:2,000	DEQ/LQD Mining Permits	digitizing
Surface Water Rights	1:24,000	Wyoming State Engineer's Office	digitizing
Ground Water Rights	n/a	Wyoming State Engineer's Office	DBASEINFO
Digital Elevation Models	30 meter resolution	USGS	DEMLATTICE
Public Land Survey System	1:100,000	WWRC	pre-existing
Transportation	1:100,000	U.S. Bureau of Census	pre-existing

feature. These attributes could be either directly tied to the data layer or indirectly accessed through relational files. For ease of use by modelers, most data layers, with a few exceptions, did not have an associated relational database structure.

Quality Control. With any modeling, a degree of data quality assurance is necessary to provide defensible results. For the GIS data layers, both spatial feature completeness and location were examined, as well as the accuracy of associated attributes. This was accomplished, in many cases, by producing a map of the data layer and comparing it to the original. This allowed for missing and/or mislabeled features to be identified and corrected. In cases where comparable maps were not available, the source data were directly compared with its GIS counterpart. Spatial accuracy of all the data layers followed the US National Map Accuracy Standards (U.S. Bureau of the Budget, 1941).

Metadata. Metadata describe the content, quality, condition, and other characteristics of data (Federal Geographic Data Committee, 1995). For each GIS data layer that had not been previously developed, metadata were completed. This allows for people, other than the creator, to understand and have reference to all the different aspects related to the data layer (i.e. data quality, type of features, spatial reference, attribute-naming conventions, etc.). This is an essential complement to any GIS data layer deliverable and accompanies the data during distribution.

Model Integration

For the pilot CHIA, GIS model integration involved modifying and querying data layers for model input and aid in spatially displaying model outputs. Future work will be directed at producing a seamless GIS connection for each model used in the assessment.

Model Input. The main focus surrounding the use of GIS data in the surface-water modeling effort was limited to developing hydrological response units (HRUs) and then querying data with reference to these units. Hydrography, slope, aspect, land cover, soils, surficial geology, and clinker (baked and fused geologic material generated during the combustion of a coal seam) data layers were all used in determining the boundaries of the HRUs. The goal during creation was to maximize homogeneity with respect to these data layers while maintaining a catchment identity. This required a multitude of overlays and several modifications before a final layer could be produced.

The HRU data layer provided the framework in which parameter estimation and/or calculations were structured. For example, each HRU had an associated attribute relating to the total channel length and drainage density for that particular unit. Additionally, a percentage breakdown of land cover, soils, surface geology, and clinker could be found within the attributes of this layer. All of these attributes were determined by overlaying the HRU layer with the necessary data layer, and applying specific calculations.

GIS played a significant role in the pilot CHIA groundwater modeling. A refined, non-equal area, cell-based grid set the data structure into which all other data layers had to be transformed before modeling could occur. This grid was developed by MODELGRID (Winkless and Kernodle, 1993), an Arc Macro Language (AML) program was designed to produce a vector-based grid with both polygon (cells) and point (cell centroids) attribute data.

The most common data manipulation involved placing vector data layers and the associated attributes into this pre-defined, irregularly-shaped grid. For example, it was necessary to determine which grid cells have 50% or more of their total area designated as clinker and differentiate those cells from the others. Other data layers such as burn line, coal faults and folds, mining sequence, and monitoring wells, all had to be incorporated into the grid with each layer having its own set of standards. These processes required extensive Arc Macro Language (AML) programming for testing and attributing each of the 5,994 grid cells based on specific criteria. Once all model input data layers had been placed within the grid, the MODARRAY (Winkless and Kenoodle, 1994) AML was used to export the data from an ARC/INFO coverage to an ASCII array format specific to MODFLOW.

Additional data manipulation was required in converting spot groundwater elevations into contours. This first involved kriging (process that interpolates a surface from a set of variably-spaced points) the data points in order to interpolate the values throughout the region. Due to ARC/INFO's limited kriging models, all kriging was performed using an external statistical package that produced a surface which could be imported back into ARC/INFO to create a contour coverage. These contours were then transformed back into the refined grid through an AML that used a weighted average method to determine each cell's approximate groundwater elevation.

Model Output. In addition to parameter estimation, GIS played a significant role in displaying MODFLOW modeling outputs. Through the use of spatial contour mapping, visual comparisons could be made between years and aquifers in relation to coal mining effects on groundwater.

Groundwater drawdown outputs produced by MODFLOW were placed back into the previously- discussed refined grid. This was accomplished through the use of AWK scripts for ASCII array manipulation, and subsequent importation of the data into INFO (the Arc/Info database system) with the cell identifier and accompanying drawdown output. Once within INFO, the table was joined to the refined grid data layer. The centroids for each cell then provided spot elevations from which a Triangular Irregular Network (TIN) was created. With an elevation TIN, the command *TINCONTOUR* was applied to produce drawdown contours for the specific MODFLOW modeled year. This process was repeated for five different years and two different aquifers.

Discussion

GIS proved to be a critical tool for completing the CHIA modeling process in an accurate and efficient manner. Building on initial methodologies, it is anticipated that the role of GIS will continue to expand in future CHIA efforts, given the enormous data-management tasks associated with each of the three remaining cumulative impact areas delineated in the Powder River Basin.

Building a Spatial Decision Support System

While certain specific data-management and analysis issues are currently being addressed by the ongoing CHIA development effort at the University of Wyoming, a broader need still exists for the development of computer-application tools capable of: 1) managing large quantities of spatial and non-spatial digital hydrologic data; and 2) providing an efficient means for utilizing such information in an integrated hydrologic impact analysis/modeling environment. The utilization of GIS can greatly enhance complex spatial problem solving. However, such systems often do not adequately support decision making because they are lacking in analytical modeling capabilities when not linked to existing models. One response to this shortcoming is the development of a spatial decision support system (SDSS) specifically designed to support a decision research process for addressing complex spatial problems. An SDSS provides a framework for integrating database management systems with analytical models, graphical and tabular display, and reporting capabilities, in combination with the knowledge of decision makers (Densham, 1991).

Supported by funding from the Wyoming Abandoned Coal Mine Land Research Program, research is currently underway at the University of Wyoming to develop an integrated, modular spatial decision support system (SDSS) for assessing the hydrologic impacts of coal mining and land reclamation activities in the Powder River Coal Basin of northeastern Wyoming. Components of the System will include existing surface-water and groundwater models (HEC-1; MODFLOW), a geographic information system (ARC/INFO GIS) and a relational database management system (ORACLE RDBMS). The overall goal in developing the System will be to provide resource managers with a dynamic evaluation and decision making tool. Applications will include model input generation/manipulation, model execution, and transfer of model-generated results into a spatially referenced format.

By integrating the surface- and groundwater models chosen for the CHIA, the SDSS will provide regulatory authorities with: 1) a user-friendly, integrated modeling software application, providing hydrologists and resource managers with the ability to pose "what if..." type questions concerning hydrological conditions without having to be GIS experts or database managers; and 2) an adaptable methodology for conducting dynamic CHIAs in any foreseeable application area of Wyoming. In addition, the SDSS will also provide a set of application tools for use by mine permit applicants in completing PHC determinations, as well as contributing to the advancement of electronic permitting methods (format compatibility, data transfer, etc.), thus making the permitting process more efficient and cost-effective for all parties involved.

Literature Cited

Densham, P.J. 1991. "Spatial Decision Support Systems", In Geographical Information Systems, Volume 1: Principles, edited by D.J. Maguier, M.E. Goodchild, and D.W. Rhind. John Wiley & Sons, Inc, New York, NY.

Denson, N.M. and C.T. Pierson, 1991. Geologic Map showing the Thickness and Structure of the Anderson-Wyodak Coal Bed in the South half of the Powder River Basin, northeastern Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-2094-B.

DeVantier, B. A. and A. D. Feldman. 1993. Review of GIS applications in hydrologic modeling. Journal of Water Resources Planning and Management, 119(2):246-247.
https://doi.org/10.1061/(ASCE)0733-9496(1993)119:2(246)
https://doi.org/10.1061/(ASCE)0733-9496(1993)119:2(246)

El-Kadi, A.I., A. A. Oloufa, A. A. Eltahan, and H. U. Malik. 1994. Use of a geographic information system in site-specific groundwater modeling. Ground Water, 32(4):617-625.
https://doi.org/10.1111/j.1745-6584.1994.tb00897.x

Federal Geographic Data Committee. 1995. Content Standards for Digital Geospatial Metadata Workbook. Federal Geographic Data Committee, Washington, D.C.

Heffern, E.L., and J.R. Oakleaf. 1996. Digital Clinker Map of the Powder River Basin, Wyoming (work in progress).

Hinaman, K. C. 1993. Use of a geographic information system to assemble input-data sets for a finite-difference model of ground-water flow. Wat. Res. Bul. 29(3):401-405.
https://doi.org/10.1111/j.1752-1688.1993.tb03217.x

Hoa, Q. and Y.P. Chugh. 1993. Spatial predictive modeling of mine subsidence risk with GIS. *In:* GIS/LIS '93: Proceedings of the conference in Minneapolis, MN, November, 1993, by ACSM, ASPRS, AM/FM International, AAG and URISA. Bethesda, MD: ACSM, ASPRS, AM/FM International, AAG and URISA, 270-281.

Maguire, D. J. 1991. An overview and definition of GIS. *In:* Maguire, D. J., M. F. Goodchild, and D. W. Rhind (Eds.). Geographic Information Systems: principles and applications. Longman, London, Vol. 1, pp. 9-20.

Maidment, D. R. 1993. GIS and hydrological modeling. *In:* Goodchild, M. F., B. O. Parks, and L. T. Steyaert (Eds.).

Environmental modeling with GIS. Oxford University Press, New York, pp. 147-167.

Males, R. M. and W. M. Grayman. 1992. Past, present and future of geographic information systems in water resources. Water Resources Update 87:5-11.

Martin, L.J., D.L. Naftz, H.W. Lowham, and J.G. Rankl. 1988. Cumulative hydrologic impacts of surface coal mining in the eastern Powder River structural basin, northeastern Wyoming, U.S. Geological Survey Water-Resources Investigations report 88-4046. U.S. department of the Interior, Cheyenne, WY.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6. U.S. Geological Survey, Reston, VA.

Office of Surface Mining Reclamation and Enforcement (OSM). 1985. Guidelines for preparation of a cumulative hydrologic impact assessment, draft. U.S. Department of the Interior, Washington, D.C.

Office of Surface Mining Reclamation and Enforcement (OSM). 1991. Managing hydrologic information in the coal mine permitting process - guidance for PHC and CHIA, draft. U.S. Department of Interior, Washington, D.C.

Parker, H. D. 1988. The unique qualities of a geographic information system: a commentary. Photogrammetric Engineering and Remote Sensing, 54(11):1547-1549.

Peacock, K., A.J. Anderson, J.R. Oakleaf, E.L. Heffern, and S.P. Gloss. 1996. Pilot CHIA Study, Little Thunder Creek Drainage, Wyoming Wyoming Water Resources Center, Laramie, Wyoming (in review).

Richards, C. J., H. Roaza, and R. M. Roaza. 1993. Integrating geographic information systems and MODFLOW for ground water resource assessments. Water Resources Bulletin, 29(5):847-853.
https://doi.org/10.1111/j.1752-1688.1993.tb03244.x

Sasowsky, K. C. and T. W. Gardner. 1991. Watershed configuration and Geographic Information System parameterization for SPUR model hydrologic simulations. Water Resources Bulletin 27(1):7-18.
https://doi.org/10.1111/j.1752-1688.1991.tb03108.x

U.S. Bureau of the Budget. 1941. National Map Accuracy Standards. U. S. Bureau of the Budget, Washington, D.C.

U.S. Environmental Protection Agency and the USDI Office of Surface Mining. 1995. 1995 Progress Report: Statement of mutual intent strategic plan for restoration and protection of streams and watersheds polluted by acid mine drainage from abandoned coal mines. USEPA, Philadelphia, PA.

Watson, W. and K. Bryant. 1993. Assessing U.S. coal resources: an integration of GIS and statistical methods. *In:* GIS/LIS '93: Proceedings of the conference in Minneapolis, MN, November, 1993, by ACSM, ASPRS, AM/FM International, AAG and URISA. Bethesda, MD: ACSM, ASPRS, AM/FM International, AAG and URISA, 738-752.

Winkless, D. and Kernodel. 1993. MODELGRID. An Arc Macro Language/FORTRAN program to develop an Arc/Info point, line, and polygon coverages from user inputs.

Winkless, D. and Kernodel. 1994. MODARRAY. An Arc Macro Language/FORTRAN program to develop MODFLOW arrays from Arc/Info point, line, and polygon coverages.

Yoon, J., G. Padmanabhan, and L. H. Woodbury. 1993. Linking agricultural nonpoint source pollution model (AGNPS) to a geographic information system (GIS). GIS & WR:79-87.