An Integrated Groundwater and Land-Use GIS for Impact Assessment

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ABSTRACT: Groundwater problems have been traditionally solved with graphic techniques. This study demonstrates the application of emerging geographic information system (GIS) technology to the solution of groundwater impact assessment problems. This application of GIS focuses on the area around Alexandria, Louisiana, along the Red River. The integrated data set of groundwater levels and land-use types allow for efficient and objective assessment of postproject impacts. The methodology will interest GIS practitioners because it integrates ERDAS and Intergraph data formats. Unsupervised and supervised state-of-the-art remote sensing techniques classified Landsat data into the land-use types. The workflow also includes tablet and heads up digitizing, vector-to-raster conversions, inputting ASCII data, and generating triangulated irregular networks (TIN) models. Analysis of the data sets applies Boolean logic. The graphic results prove that GIS is a powerful tool for environmental and hydrogeological scientists.

INTRODUCTION

PURPOSE AND SCOPE

THE PURPOSE OF THIS STUDY is to demonstrate the use of geographic information systems (GIS) to evaluate the effects of navigational pools on groundwater conditions and assess any actual post-project land-use impacts. The area of this assessment is in the vicinity of Alexandria, Louisiana, along the Red River. The objective of this paper is to describe the groundwater problem and the GIS method for efficient evaluation of impacts.

PROJECT HISTORY

The U.S. Army Corps of Engineers is in the process of constructing five locks and dams on the Red River as part of the Red River Waterway Navigational Project (Figure 1). The resulting navigational pools will cause higher stages in the river during low and medium flow periods. Because the Red River Alluvial Aquifer is in direct hydraulic connection with the river, the outflow from the aquifer to the Red River will be reduced due to the reduction in head differential. This decline in outflow will cause groundwater levels to rise also. Alexandria, Louisiana, is the largest urban area adjacent to pool 2. The design pool at elevation of 64 feet was established in February, 1989. Therefore, the Alexandria study area offers an opportunity to evaluate effects of the navigational pool ,i.e., the changes in groundwater levels and impacts to land use activities that have occurred since the rise in navigation pool in February, 1989.

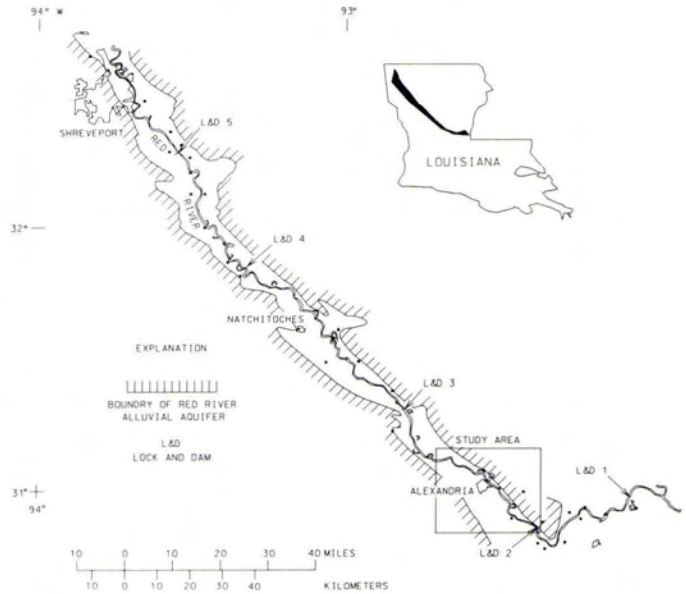

FIG. 1. Location of Red River Waterway.

PREVIOUS WORKS

The United States Geological Survey (USGS) began preliminary investigations as early as 1962. The USGS data collection and cooperation with the Corps is continuing. A Summary of Ground Water Studies by the USGS 1962-1985 is available (Rogers,1988). The USGS installed a network of observation wells in the Red River alluvial aquifer for a background preconstruction database. The database was used to calibrate numerical computer models to simulate post-project groundwater levels (Ludwig and Terry, 1980). Output from the models was used to make post-construction groundwater level maps for the alternative lock and dam locations and pool elevations (Ludwig, 1975). The USGS has collected and maintained the historic groundwater level database (Smoot and Guillot, 1988). Comparison of pre-construction and post-construction water level data will be the final determination of project induced change. The database was also used for the Soil Conservation Service (SCS, 1977) and D'Appolonia (1980) assessments of predicted groundwater impacts.

The SCS has responsibility for evaluating the effects that raised groundwater table levels will have on agricultural crop lands. These evaluations were made using pre-project, and predicted post-project, groundwater table levels developed by the USGS. The response of crops, pasture, and trees to fluctuating water table levels was evaluated using crop observation test sites. The changes in yields observed on different soils were correlated with river stage and water table level changes. These relationships were used for the calculations of predicted post-project effects on plant growth and yield (SCS, 1977). The conclusions

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reached were for the pool areas as a whole. The evaluation was general in scope, because site specific assessment was avoided.

D'Appolonia (1980) expanded upon the earlier work of the USGS and SCS, and went further to assess the impacts on rural and urban areas. The rural evaluation was displayed as tables and maps with decrease/increase impact shown in 40 acre cells. The findings of the D'Appolonia study were presented in the Environmental Impact Statement (EIS) Supplement # 2 with updated 1982 costs. The assessment was a good prediction of probable post-project impacts. Although less general than the earlier USGS and SCS studies, the impact maps cannot be used to determine precise impact to acreage of small plots (less than 40 acres) but can be used to estimate overall acreage adjacent to the pool with reasonable accuracy. Therefore, site specific quantitative impact assessments are not available.

Geology

The Red River occupies an entrenched alluvial valley. The Red River Valley is incised into Tertiary age deposits which outcrop in the adjacent uplands. Throughout the Quaternary period the Red River has alternately degraded and aggraded its valley in response to climatic variation and change in sea level. The resulting alluvium is characterized by a fining upward sequence of gravel, sand, silt, and clay with a combined average thickness of 100 feet. Figure 2 illustrates the general features of the alluvium in the subsurface in the Alexandria study area. The basal portion of alluvial sequence constitutes the alluvial aquifer. This sand and gravel unit is known as the substratum. The Corps uses the term topstratum to describe the upper fine grained portion of the alluvium. The topstratum comprises the confining bed above the aquifer. The tapestry of topstratum woven by the meandering Red River is differentiated into environments of deposition (Smith and Russ, 1974). The thickness of the topstratum and substratum varies from place to place according to depositional environments.

Hydrogeology

The hydraulic characteristics of the Red River Alluvial Aquifer vary widely depending on the above mentioned depositional environments. The water budget or hydrologic cycle of the Red River Valley is described below. Water enters the alluvium by (1) infiltration of rainfall, (2) recharge streams during high stages; and (3) recharge from adjacent and/or underlying formations. Most of the recharge is infiltration of rainfall. The annual rainfall in the Alexandria area is 56 inches. Most precipitation occurs from December through May and the least precipitation occurs from September to October. Thus, the high groundwater levels are in the spring and low levels in the fall. Water in the aquifer is confined by overlying fine grained topstratum. The aquifer acts according to artesian principles due to the orders of magnitude of difference in hydraulic conductivity between the confining topstratum and substratum aquifer. Although local recharge to the aquifer from streams occurs during high stage,

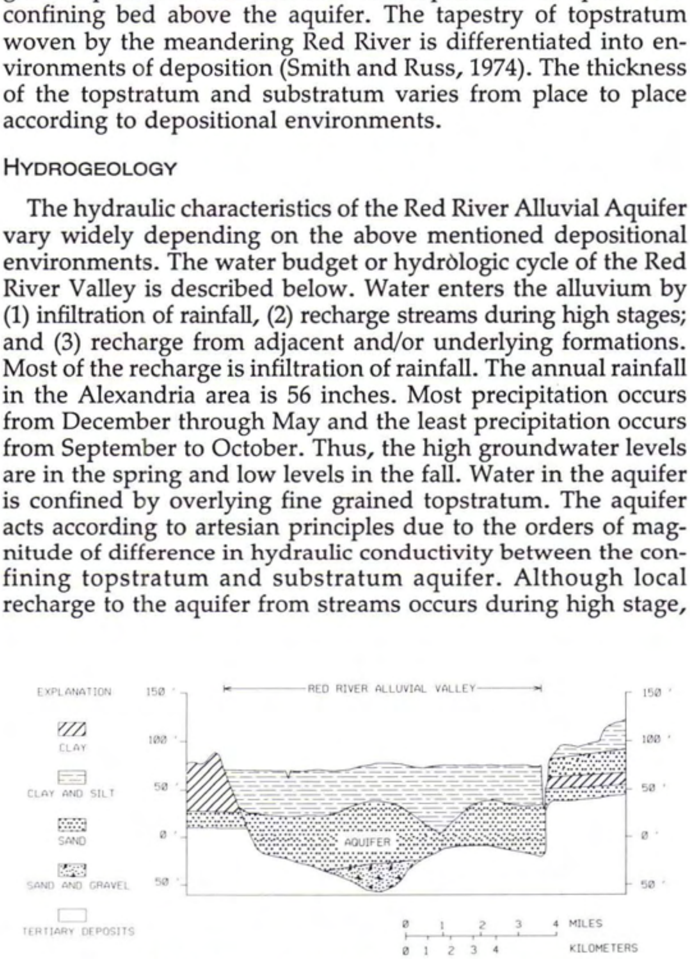

Fig. 2. Geologic section, Red River Valley (from Rogers, 1983).

the streams usually act as discharge sinks. Therefore, inflow is discharged to the Red River and its tributaries, unless expired through evapotranspiration.

The hydrologic feature of interest in the flow system for this study is the change in water level in response to changes in new boundary conditions due to the impoundment of the navigational pool. The Red River alluvium has a dynamic flow system, with water levels changing continuously in response to the internal and external factors affecting recharge or discharge. The internal factors of conductivity, transmissivity, and storage are unchanged. External factors such as amount of precipitation and rates of evapotranspiration are assumed to be unchanged or similar to preproject conditions. The change in the flow system is the new minimum stage of the Red River.

Problem

The problem is how to evaluate the change on groundwater conditions and conduct objective evaluation of land-use impacts. Initially, the vast amount of data and the varied approaches of previous investigations made the problem overwhelming. Besides examining the changes in groundwater levels with cross-section or elevation/time plots, potentiometric maps were compared. The previous studies produced potentiometric maps of pre-project and predicted average at different scales. Actual post-construction potentiometric maps were constructed either by hand, or by using commercial contouring packages. Comparison of these maps made conclusions difficult and time consuming. Site specific assessment with shorter evaluation time required a more efficient method.

Geographic Information System Application

A microcomputer geographic information system (GIS) was selected to demonstrate how this technology could store, access, analyze, and portray this vast amount of pre-project, predictive, and actual post-project data. The GIS acts as a unified relational database that ties together each level of information by a common geo-referenced grid array. In this case the array or raster projection is Universal Transverse Mercator (UTM). The UTM system was selected over longitude/latitude for ease of arithmetical analysis. The size of the study area was initially agreed to be the "B Map" of the D'Appolonia (1980) report. The resolution of each raster grid was selected at 50 metres. The resolution at 50 metres is approximately an acre which is suitable for the degree of site specific assessment needed for the study's purpose.

Data Input and Interpolation

The first level of information inputted was the ground surface elevation (NGVD). The data were digitized inputting 10 foot contour lines from 1:62,500- and 1:24,000-scale USGS quadrangles. The topography was created in two scenes which were subsequently merged. A seamless map is one of the practical points and benefits of a GIS. The pre-construction (Ludwig, 1975) potentiometric map was digitized. The resulting map consists of average 2-foot contours. The USGS predicted pre-construction potentiometric map was also digitized. The *x,y,z* files contain approximately 5,000 known points. The unknown area was then interpolated with an octo-linear procedure. The interpolation thus cuts synthetic "*z*" to fill in the remainder of the 500,000 points or pixels in the scene. Another method of input consisted of transferring *x,y,z* data files from the USGS database in ASCII format into the GIS. In this way 50 actual post-project water levels could be inputted, and interpolated into a real time groundwater surface as elevation or depth.

Land-Use Classification

Another input variable of the integrated groundwater impact study was land-use type. The SCS (1977) established critical water levels for each crop type which would either reduce or increase crop yield. These critical threshold water levels were assigned to each land-use class. The land-use maps identify all land-cover classes in the study area with a major emphasis on identifying cotton, corn, and soybean fields to determine how these crops were impacted by groundwater levels based on root depth. The pre-project 1979 land use was taken from the D'Appolonia data. Each of the 11 land-use categories were digitized as closed polygons with each polygon assigned an appropriate attribute.

The post-project 1989 land use (Plate 1) was added to the database from Landsat Thematic Mapper digital data acquired on 8 August 1989. All image processing required to produce the classified map was accomplished on a COMPAQ 386 using ERDAS/ISODATA digital image processing software. ISODATA moves candidate pixels vectors from one cluster to another in such a way that the sum of the squared error is reduced (Richards, 1986). Once the clusters were defined, the mean digital count, covariance matrix, and transformed divergence were computed. Clusters that were not spectrally separable were either deleted or were merged with other clusters. There is an inverse relationship between statistical separability and probability of error. The smaller the probability of error, the greater the statistical separability of the clusters (Swain, 1978). In this study there were nine separable classes: water, forest, forest wet, cotton, corn, soybean, pasture, bareground, and urban. A per-pixel maximum-likelihood classification was then carried out for the entire study area using these nine classes. The last step was to test the accuracy of the classified file. Ground verified test fields were picked from the raw data set representing each land-cover class. They were then compared to the classified file and were found to exhibit a small amount of error.

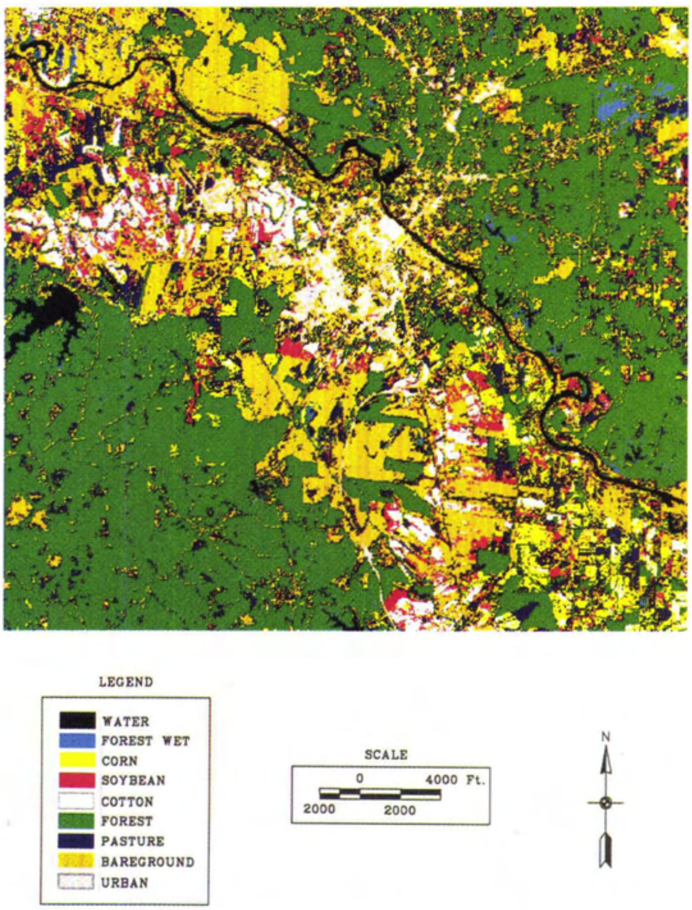

PLATE 1. Land-use 1983 classification from Landsat scene.

INTEGRATION

The initial microcomputer demonstration of GIS was acceptable to test the application of the technology. Expansion of the study area and sponsor's decisions lead to transferring the unified database to an Intergraph workstation. The following describes the workflow of data translation and database expansion. The most cost-effective source of data was to use the work that had already been done. A conversion process had to be outlined to convert ERDAS data to the Intergraph. Additional information was inputted by digitizing on a tablet. This vector input routine was easily converted to a raster format and "added" to the existing data to cover the entire study area. A group of scanned 15-minute maps was used as a backdrop for digitizing and the addition of vertices to a triangulated irregular network, or TIN model. These 3D models were the basis for the generation of contours (Figure 3), or 2D grid files were used to represent both surface elevation and water level at a given time. The initial vertices for the TIN models were derived from data obtained from the USGS PRIME GWSI database. These spatial data are also tied to a local database for easy future reference.

ANALYSIS AND RESULTS

There are a few factors which should be considered before analysis. As in most raster GIS systems, the rotation and skew of the data sets must be the same before any overlaying processes can be achieved. Each pixel of a grid has certain values associated with it. The range of values allowed for a grid file depends on both the User Type Code (UTC), which determines

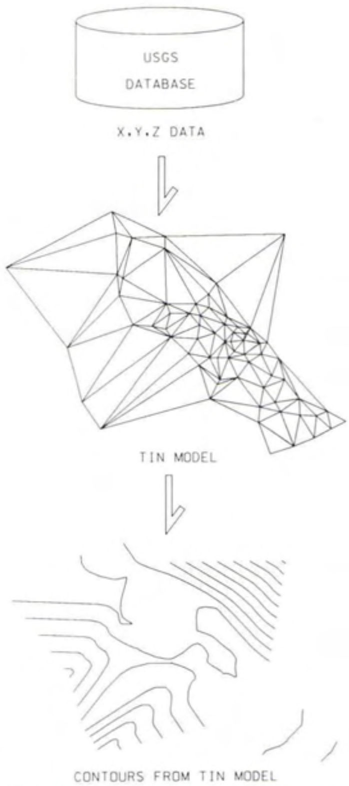

FIG. 3. TIN and contour models used for potentiometric surface generation.

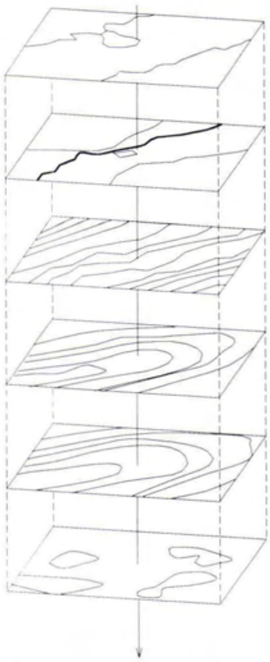

FIG. 4. Graphic depiction of impact assessment.

whether the file is signed or unsigned, and the Data Type Code (DTC), which determines the number of bytes per cell. Every grid must be warped or stretched to fit the projected design file of the area of study. Warping simply distorts the grid to conform to the selected projection being used.

After the grids have been manipulated and are ready to be used in an analysis scheme, an analysis language is applied to produce results in grid form. Intergraph's GIS-Oriented Analysis Language (GOAL) is a simple programming language used to control the operation of several GIS analysis operations. It serves several operations such as Overlay and Multiple Regression Analysis. GOAL's methodology is similar to BOOLEAN operation script. Basically, Boolean algebra is deductive reasoning by conditional comparison statements such as *and, or, not, less than*, and *greater than*. In this way, GOAL scripts can search out multiple conditions.

First, pre-project water elevation is compared to the topography. The procedure was repeated for predicted post- project conditions. Comparing the two shows how wet conditions will increase based on the USGS model studies. The results are exaggerated because the predicted water levels are average. As mentioned earlier, the low readings are affected; therefore, the averages levels are also affected. The wettest condition during post-project period will be the same as before. Also, actual post-project data portray less affected areas. Thus, the preliminary results reveal that impacts are less than predicted. If one reviews the final results of the Tennessee-Tombigbee Ground Water Study (Bryan, 1985; SCS, 1989) the same conclusion is reached, i.e., the effects due to water logging are over-exaggerated.

This brings the interpretation to the point of impacts. So far, the effects of the project to groundwater levels have been discussed. Impact is the result of a post-project effect that reduces or increases the land-use activity. This is why the 1979 and 1989 land-use classes were included in the GIS. The resulting output graphically portrays land-use areas that have crossed the threshold of impact. The final assessment procedure (Figure 4) utilizes actual data instead of predicted data and is fine tuned at a one-acre grid (50-metre resolution) instead of 40-acre cells.

SUMMARY AND CONCLUSIONS

Alexandria, Louisiana, is a large urban area adjacent to Red River Waterway Pool 2. This area was chosen to demonstrate the use of GIS to evaluate groundwater impacts. The integrated GIS consists of pre-project and post-project groundwater levels, ground surface elevations, and land-use types. The analysis evaluates these multiple conditions to conduct impact assessments. We can conclude from our analyses that (1) GIS is an efficient and objective method for comparison of varied data sets through time; (2) GIS technology has demonstrated its use as another analytical tool for groundwater assessments; and (3) the demonstration of GIS has only begun to tap its power and potential. Because this is a continuing study, this is not the first work or last word on the Alexandria Assessment or the application of GIS to groundwater questions.

ACKNOWLEDGMENT

The tests described and the resulting data presented herein, unless otherwise noted, were obtained from research conducted under the Red River Groundwater Impact Study of the United States Army Corps of Engineers by the Engineering Geology Branch, Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station for the U.S. Army Engineer District, Vicksburg. Permission was granted by the Chief of Engineers to publish this information. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

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SOFTWARE REVIEW

SPACE-90 Satellite Launch History Software

Product Information

Software Name: SPACE-90, Version 2.0
Release Date: 1990
Developer: Joseph J. Burger
Vendor: Space Analysis and Research, Inc., 6957 Blackhawk Place, Colorado Springs, CO, 80919-1124; Phone: (719) 260-0500
Single Copy Price: $75 for Basic System for single user; $55 for 1-year update to Basic System; $100 for 2-year update to Basic System; $140 for Complete System; $65 for 1-year update to Complete System; $120 for 2-year update to Complete System.
Distribution Medium: Three 5¼-inch floppy disks

Hardware Requirements

Computer Platform: IBM PC
Operating System: MS/DOS 2.0 or later
Minimum RAM Required: 512 Kbytes
Hard Disk Space Required: 1.5 Mbytes
Floppy Drive: 5¼ inch for software installation and updates

SPACE-90 is an on-line database containing information about almost every vehicle launched by various space programs throughout space exploration history. Beginning with Robert Goddard's early rockets and continuing through the German V-2 program to the current international programs, SPACE-90 represents a collection of data from disparate sources including NASA's Satellite Situation Reports, the Royal Aerospace Establishment, and the Soviet Year in Space data, to name a few. Because the space community has never enforced standards in their documentation of missions, SPACE-90 contains a data access expert system to facilitate access to users who are not familiar with all the details of the more than 5,000 launches.

The system can be purchased in both the Basic and Complete form. For the Basic System, more than 5,000 records exist with information about the names, launch numbers, dates, times, owners, etc., for each of the launch activities. For the Complete System, each object or record contains a brief description with information on date of booster failure, nature of scientific mission of the satellite, etc. To maintain current information, updates are sent to the user on a quarterly basis per year.

The vendor provides a companion product to SPACE-90 named CATSAT, an on-line database containing information about all the man-made objects which are known to have been placed in space by the various space agencies. The information was derived from the U.S. Space Command and NASA. The software is basically a database management system (DBMS) that allows the user to find these man-made objects by using various search keys such as catalog number, international number, launch date, owner, site, and decay date, as well as other search parameters.

FEATURES

SPACE-90 enables the user to search for data based upon several categories of information including name, catalog number, month or year, owner, mission, launch site, booster type, orbital inclination, transmission frequencies, geostationary position, and by which astronauts were on board (i.e., in the manned case). Moreover, for the often abstruse former Soviet Union space program, a small expert system is provided so that the user can find data based upon imprecisely specified query information.

All the queries are created from the main menu which asks what category the user wishes to use in accessing information (e.g., by name, owner, etc.). After that selection, the user is asked to input information such as the time range for operation, launch, or some other parameter. Eventually, the system responds by returning data back in the typical database format of a table with the rows being the entries and the columns being the relevant information such as name, catalog number, owner, apogee, perigee, and other parameters.

PERFORMANCE

SPACE-90 was installed and tested on an IBM PC with an Intel 80286 microprocessor. As mentioned before, queries to the database are formulated from user input in response to several