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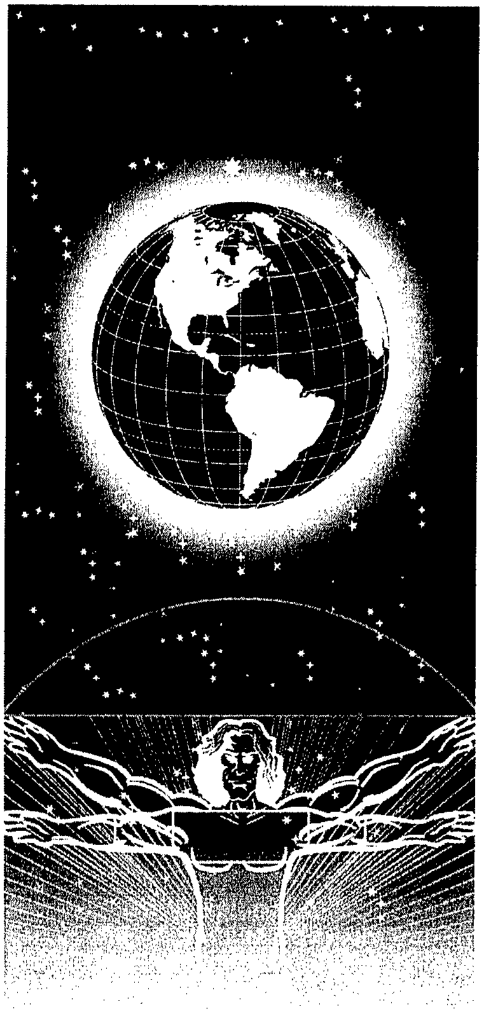

UNITED STATES AIR FORCE
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A Critical Review of GIS Uses Related to the United States Air Force Environmental Work

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January 2001

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This paper describes and assesses the uses of Geographical Information System (GIS) and methods that provide inputs to GIS to aid environmental decision-making in many aspects of envirionmental risk analysis (R/A) under the USAF intiative for environmental work. Sound science and reliable "tools" used in environmental work to calculate risk and to reduce the often-large uncertainties in environmental and health risk analysis can be coupled with GIS.

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EXECUTIVE SUMMARY

ABSTRACT

This paper describes and assesses the uses of Geographical Information System (GIS) and methods that provide inputs to GIS to aid environmental decision-making in many aspects of environmental risk analysis (R/A) under the USAF initiative for environmental work. Sound science and reliable "tools" used in ENVIRONMENTAL WORK to calculate risk and to reduce the often-large uncertainties in environmental and health risk analysis can be coupled with GIS.

PURPOSE

The purpose of this paper is to assess the usefulness of GIS in the context of environmental work. The approach taken to meet that purpose consists of following assessments:

1. The use of GIS in environmental work and decision-making

2. The benefit of using GIS in a broad environmental context, and

3. The development of a homogeneous template for assessing the literature and the use of the template to describe commonalties and the differences among the several environmental studies that have used GIS as their core methodology.

The rationale for this approach is that the Air Force stakeholders who use GIS in the context of environmental work can become more confident in the potential short-and long-term outcomes of their managerial choices.

The fundamental conclusion from this work, the result of a survey of the literature and the analysis of several environmental case studies that have used GIS, is that:

- The case studies uniformly show that GIS unequivocally is an essential tool for analysis, synthesis and decision-making in environmental and health risk analysis and assessment, as well and other domains of relevance to the US Air Force environmental efforts.

A summary of the issues and uses of GIS, and tools that can input into GIS, indicates that:

- GIS can be coupled to different external models (such as ground water, air and other transport and fate models) and use their outputs to describe the areal and temporal locations of pollution and risks. This physical, chemical and environmental information base can be coupled with demographic and other factors to provide a readily comprehensible and complete visual description of the relationships sought by the decision-makers. The information generated by GIS can reflect the dynamic aspects of the relationships, in suitably discrete intervals of time, as well as the uncertainties associated with the inputs and outputs. In this context, the USAF environmental work provides some of the critical components to make the GIS a powerful tool for the USAF.

- Using GIS requires capital and labor costs and specialized expertise in the required domains of knowledge relevant to environmental decision-making. Given the wide variety of environmental decisions confronting USAF's management, the tools for risk assessment go hand-in-hand with GIS analyses.

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INTRODUCTION

GIS is software: it is a special case of information systems and data bases that relies on the man-machine interface because it uses people and judgment directly through computer-supported queries and then displays that information in such modes as real-time on a spatial domain.

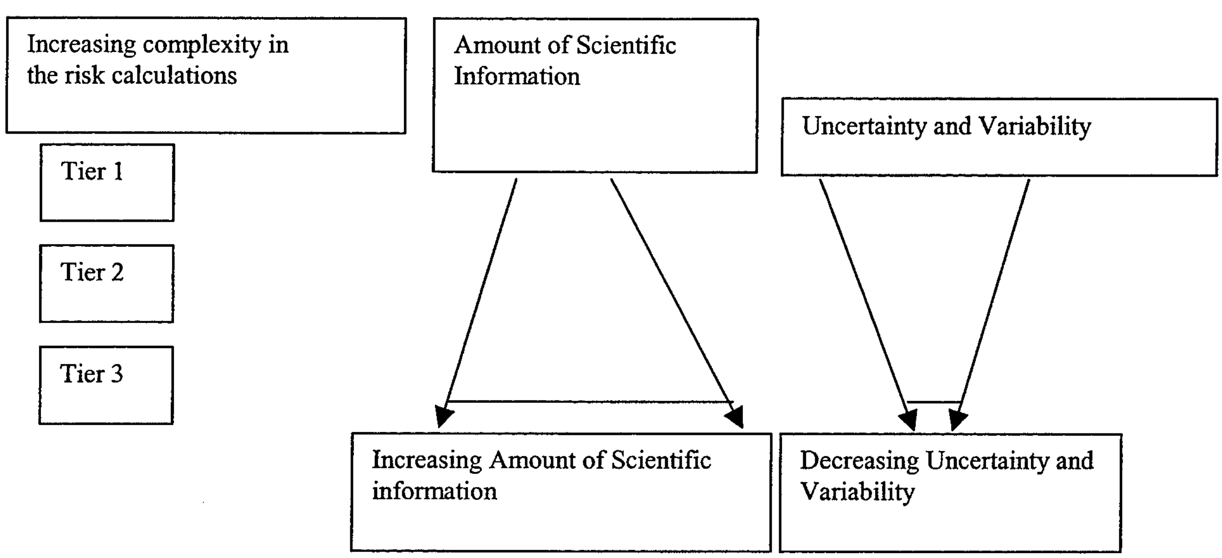
Conceptually, a GIS is a mapping of raw and often-heterogeneous information into meaningful, compact and useful outputs spatially. As such, the USAF can use it as a problem-solving tool for evaluating:

- Environmental risks
- Human risk, and
- Cost avoidance measures.

To do so, the USAF has articulated environmental work on three-tiers (see Figure 1). The level of analysis increases from tier One to tier Three. Assuming defaults, such as done in screening risk assessments, can subsume uncertainty but so doing can decrease the confidence in the decisions take, particularly when uncertainty and variability are large, relative to the central values of the variables used in the screening assessment. Generally, however, Tier One assessments plausibly determine the bounds of the risk and avoid further costly and more complex analyses.

The defaults can be dropped and substituted by state-of-the-art scientific knowledge in Tier 2 and Tier Three assessments. When this is done, and such is clearly considered within the scope of application of environmental work and its toolbox, the result is graphically depicted next:

Figure 1. Illustration of USAF environmental work articulated on three-tiers.



In this diagram, the *amount* of site-specific data *increases* as more knowledge becomes available; at the same time, the *variability* - such as the variability due to the data -- decreases. The limit to the decrease is the random noise associated with sampling plans or with the natural variability of a population. environmental work provides the means realistically and correctly to reduce both variability and uncertainty. It is often convenient to use *uncertainty* when dealing with limited knowledge about the true mathematical form of a model, such as the form of a dose-response model for leukemia. A classical example of uncertainty is the choice of a linear model versus a non-linear dose-response model for cancer risk assessment. The combination of environmental work and GIS provides the means to show the *variability* and *uncertainty* in representing scientific knowledge required for consistent and coherent environmental decision-making.

environmental work is the framework for analysis of an environmental system. The core of the flow of the information is achieved by using GIS. It works with data analysis methods (statistical and probabilistic), management actions and outcomes, static and dynamic display of information, and prediction. GIS-based approaches provide the tools needed to characterize and describe information. However, more is needed: classical GIS must be extended by an integrated view of the need of environmental work. We call this extended GIS *Meta-GIS* because it integrates within a GIS environment the critical - as opposed to all - tools needed to accomplish the USAF environmental mission under the law. These, of course, are the tools included in the tool box built in environmental work, as well as other tools, as the case might be.

Specifically, META-GIS provides the methods to reach qualitative and quantitative comparisons that can be used in making predictions and inference. Generally, GIS computer software does not provide the tools for inference or predictions necessary and sufficient to meet the environmental management demands imposed on the USAF by stakeholders. Although some GIS software includes certain statistical algorithms (such as regressions and descriptive data analysis), those statistical capabilities can be inadequate for risk assessment and economic analyses as envisioned under the environmental work Tiered systems. Thus, statistical tasks are left to such external programs as SPSS, SAS, and the like. Similarly, GIS software does not use mathematical algorithms for integrating differential equations, solving linear or other programs for allocating resources under constraint, leaving these tasks to specialized programs such as Stella, Mathematica, Matlab, LINDO and so on. Finally, GIS does not provide decision analytic tools, such as decision trees, influence diagrams, and others.

The fact that GIS software does not have these capabilities is not a drawback. Indeed, it would be far too costly, complicated and often unnecessary to include a very large number of models and computer codes within a single framework. The critical contribution of GIS to environmental decision-making is that the inputs from those models can be displayed as a GIS output. For instance, the plume of a pollutant in the ground-water modeled by a 3-D model such as TRACR3D, its path in an unsaturated environment can be displayed through a GIS and coupled to a 3-D view of wells, orchards and other salient topographical features, as well as population densities associated with future development.

GIS as a Critical Tool for Decision-Making within environmental work

GIS can be applied to both human and ecological risk assessments and management, as required by environmental work. An important function of GIS is to describe where habitat boundaries are and to predict how those boundaries can change from human or natural interventions. An example of the description is monitoring the "patch" size of natural vegetation, whereby natural habitats become fractionated and their area decreased thus affecting food supply. This description can be achieved using remote satellite imagery (at different wavelengths), Global Position Satellites positioning, field studies, and so on. The cause of the fractionation can be studied as a function of the base-line "potential undisturbed habitat" and as a function of human development, in discrete events and time periods.

GIS is a means to organize, display, describe, assess, deterministically predict and statistically forecast. It does so by allowing the:

- Formulating and recording specific scenarios or game plans,
- Helping to set priorities over geographic areas, and time intervals.
- Displaying 2-D and 3-D information, as well as information over incremental time horizons (these can be in continuous time or discrete time, depending on the choice of representations and approximations).
- Displaying multiple positive and negative outcomes, given a set of scenarios.
- Displaying benchmarks and related those to potential outcomes.

As an example, GIS can help in conservation strategies can be using GIS by contributing to the solution of basic issues such as areal and temporal identification, storage of information, modeling changes, sensitivity analysis and predictions for

- Wildlife protection
- Conservation areas
- Potential versus actual habitat restoration:
- Identification and inventory of protected areas
- Identification and inventory of unprotected areas
- Developed and development areas
- Identification of gaps by area and by function
- Overlap of gaps in time and over the geographical areas identified

The temporal aspects of decision making that can be greatly helped by GIS are the immediate-term, short-term, and the long-term. The areal aspects are essentially limitless. Specifically, the site-specificity of the Air Force's environmental work suggests an adaptive and resilient decisional framework under a number of environmental statutes, such as CERCLA, that can be readily updated under such legal instruments as ROD. environmental work, under federal and state environmental law, is used to:

- Assess the emissions, fate and transport of chemicals, and
- Analyze the consequences from exposure through human health and ecological risk analysis.

This can be achieved by coupling GIS to environmental, demographic, economic or other models such as risk models. In terms of decision-making, GIS contributes in unique and critical ways to the:

- Communication of information about human and environmental risks,
- Providing for consistency in the choices of options and alternative,
- Exhaustiveness in the selection of scenarios and choices,
- Completeness of the enumeration of scenarios and choices,
- Consistency in using and displaying uncertainty measures.

In terms of prediction and inference, should these be needed, GIS provides probably the most suitable system to portray them. Although the statistical capabilities of the GIS used in the studies reviewed in this work are limited, the computational environment provided by GIS is well suited to represent that information with either relatively simple descriptions or more complex ones, depending on the decision-maker needs. In particular, although specialized mathematical models and statistical models have graphing capabilities, these capabilities can be connect to a GIS to enrich the overall displays of information. The output of these models can be imported into a GIS to overlay the relationships between different factors.

The literature suggests that GIS has a number of external constraints. Those constraints are inherent to most, if not all, GISs and include:

- Empirical data used in GIS work is variable thus requiring statistical representations of the results.
- Gaps in the data require complex methods for imputing reliable values to the missing data.
- Scientific knowledge can be incomplete thus requiring conjectures that, once made and displayed, can be forgotten, although their footprint is indelible.
- The required computer-based models can be gross approximations of the true (but unknown) relationships displayed in the practical applications of GIS.
- Data used in risk assessment are heterogeneous (individual heterogeneity, spatial heterogeneity and so on) requiring complicated statistical inference from the group to the individual.
- The cost and human resources needs are significant.
- Training and communication to management and other stakeholders requires time and effort on the part of the developer of the GIS results.

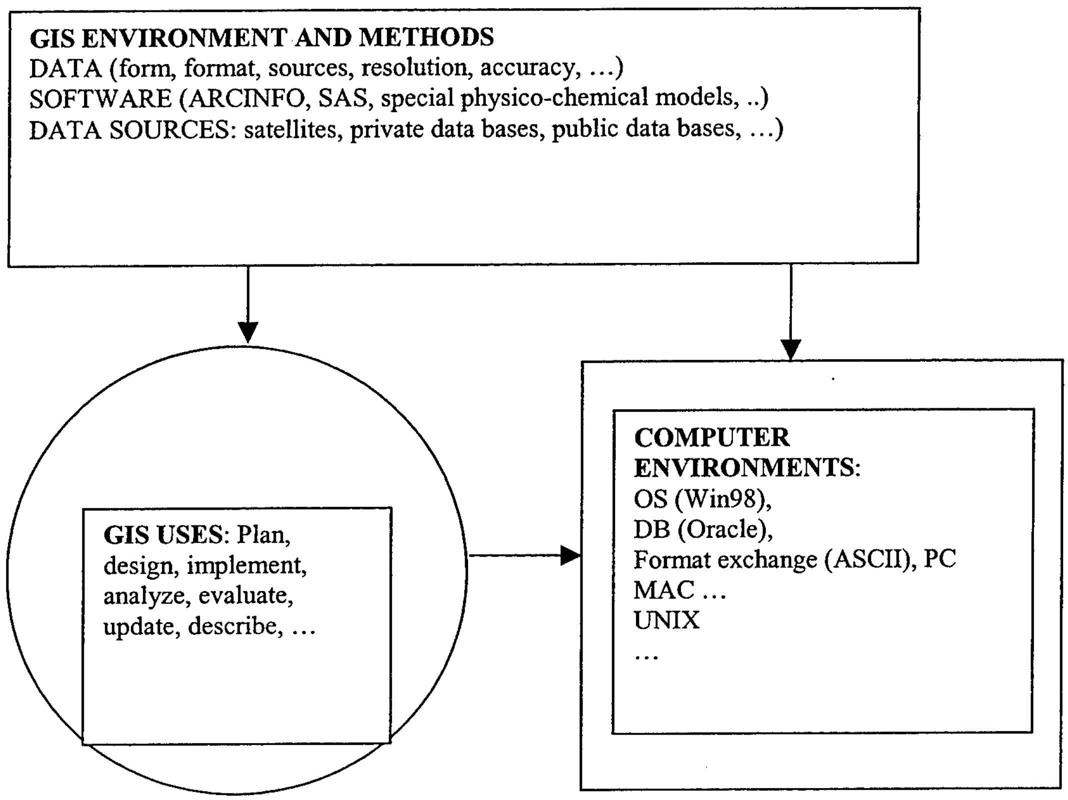
Discussion

There is much growth in the resolution, accuracy, ability to describe geographical or geophysical elevations, areal and temporal coverage, and in multi-spectral analyses. These capabilities, as well as the many types of data from one or more sources external to the GIS-proper environment are collected from many different sources and institutions. The capabilities extend to include real-time data acquisition by laptop computers or smaller devices (such as hand-held palm devices).

This increase in data gathering - often in real-time -- capability can overwhelm the analyst because it requires considerable technical knowledge in the methods to deal with those data and because of the time and effort that such analyses can take. For this reason, it is imperative to enhance raw data analysis capabilities through adding specific tools that can be used to synthesize and reduce complex data patters (e. g., statistical methods as factor analysis, classification and regression trees, pattern recognition, and so on) before depicting them through GIS. In this context, GIS can greatly help integrate and display natural resources and man-made inventories, account for specific areal, line and point sources, pollutant fate and transport, species birth/death processes, demographic and socio-economic data, as well as help the exchange of information among the stakeholders.

As shown in Figure 2 the essence of the GIS elements found in the literature can be reduced - with much simplification -- to:

Figure 2. The basic elements of GIS elements reduced from the literature shown here diagrammatically.



GIS combines the deterministic aspects of data acquisition, management and display with statistical and other methods that permit robust predictions and inference from sample data to populations at risk.

The purpose of the methods that can be "hooked" onto a GIS system to make it relevant to the USAF needs under environmental work include assessments based on:

- Deterministic methods (methods that do not involve distributions and take any number as being without variability) or statistical analyses (by definition based on random variables characterized by different distributions).

- Statistical propagation and fusion of the probabilistic uncertainties or other forms of uncertainty in a series of sub-modules that describe management options and outcomes using, for instance, Monte Carlo, bootstraps and Gibb's sampling methods.

These considerations support using GIS, within environmental work and its tool-box. In the next Section we consider some of the situations in which GIS has been used and discuss the essential lessons learned in studying those cases.

SUMMARY OF SUCCESS STORIES USING GIS

Overview

GIS has been shown to be a very useful toll in a number of different sectors of environmental work. The material discussed in this Section is based on several studies, which are not reported in a Template format for simplicity. The main point of this Section is to indicate the wide range of successes in using GIS in a variety of different contexts. The reason for this optimistic outlook is that the benefits from using GIS far outweigh the costs of implementing and using it.

A master template was developed *before* the literature review was completed. The reason for developing the template was to identify the ideal set of information that would allow drawing scientific conclusions about the successes of the studies reviewed. Unfortunately, the heterogeneity of the information reported in the studies and the budget allocated to this work prevents a formal scientific study. The templates included developed in this work provide additional specific information from several case studies in which GIS was used.

PG&E Study of Transmission and Distribution Poles

Pacific Gas and Electric (PG&E), in San Francisco, California, used Oracle data base for the relational data aspects of each pole in terms of state, position and need for maintenance. The GIS was used to inventory and maintain records of transmission and distribution poles in Northern California, approximately 2.4 million poles. These records were not available before 1994. However, increased health and safety concerns with the risks associated with the poles, as well as their total costs (capital and maintenance) convinced PG&E to embark in a major project to identify, label and establish the geographical coordinates of each of its poles. A risk-cost-benefit assessment was also developed to establish the potential liability from exposure to the chemical treatment of the poles, since the poles are often on private residential properties. The relational data base accounts for the type of pole, life of the pole, its state, need for maintenance or replacement, geographical position.

The data base consisted of reviewing each drawing, making digitized maps that could be viewed in an a hand held computer, Telxon 114DX, using Field Note Manager. The maps were calibrated using the California Grid Coordinate System; the poles were related to that grid. Each pole was visited and diagnosed for structural stability, state and so on; dangerous poles were tagged and identified for removal and replacement. This work provides significant benefits to PG&E. It allows this Corporation to accurately budget its activities, an item of considerable importance in light of the privatization of the utility industry, whose residual monopoly power the transmission and distribution of electricity, rather than the more traditional power generation.

El Toro Marine Corps Air Station: noise pollution

This base, in Orange county, CA, was closed in 1999 and its airport will be used for civilian purposes, the rest of the Base is to include a business park, a wildlife refuge a habitat preserve two golf courses an a regional park.[1] Keeping track of the impact of those changes and the ever-increasing air traffic has been facilitated using GIS, with scientific and demographic data. For instance, the community noise levels associated with air traffic used data from Marine Corps flights as well as the potential noise levels from commercial aircrafts - the planned operations for the airport. GIS was used to compare the isopleths of noise (the noise contours were measured and portrayed in decibel units) between past use and the forecast modes of aircraft operations. ArcInfo and ArcView 3D were used in this work, as was web-access. According to the source, ArcView is "really exciting" because it allows 3-D displays (GIS modeling was done by Psonomas, a company in Cost Mesa, Ca).

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[1] C. Henry, Navigating controversy, Earth Observation Magazine, July/Aug 1999.

Another aspect of this study identified the relationship between the lights associated with the two golf courses for nighttime operation. They were described using GIS for nuisance, potential interference with the flight patterns and attract birds (thus potentially being of danger to the airplanes and helicopters). In the end, "GS provided a strong analytical and scientific foundation for the planning process underlying the Master developmental program and the for the Environmental Impact report ... (Henry, 1999)). It became clear that the visual images were most successful as both having scientific credibility ("GIS lends an air of credibility to anything you present" (Henry, 1999)) and clarity to the overall patterns of noise.

Hazard Management in Storm and Other Natural Events

Early Warning System. GIS can aid the speed for making decision under contingent and rapidly evolving events. For example, Dopler radar data are critical to tracking and identifying storms and other weather events. The radar identifies the vortices as signature, giving approximately 20 minutes of early warning before a vortex reaches the ground. The problem is not the prediction of the vortices and their impact, but rather, the communication of the prediction to those likely to be affected. The radar signatures can be plotted on a map, using GIS, and on the same map plot the phone numbers of those at imminent risk. Buffer areas can also be identified depending on the severity of the hazard and the potential for exposure. The combination of these information can be used automatically to dial those at risk, in the danger areas and in the buffer areas, with pre-recorded messages (GIS Frontiers, 2000).

Imaging. Real-time monitoring and mapping of floods and areas at risk from satellites has become possible with synthetic-aperture radar because of the all-weather imaging of these systems (Corbley, 1999)[2]. This technology, implemented on such systems as RADARSAT and ERS, gives the decision-makers the ability to "see" water and land boundaries during adverse weather conditions. This information is critical in the event of flash floods and the data itself is important to predict floods, thus providing information for planning activities.

Ouachita Parish in Louisiana received approximately 10 million dollars to develop plans to deal with natural and man-made hazards (Sappington, 1999) Similarly, the City of Seattle, WA, has assessed the scale of the potential hazards in the Puget Sound using GIS data, using ArcView. The data, plotted on the US GS maps, was useful in developing an assessment of the vulnerability of transportation to natural hazards and also used to raise the awareness of the potential magnitude of those hazards to residents (Sappington, 1999).

A common tread in disaster management programs, as the successful implementation of mitigation plans and their implementation, points to GIS as the basic and most useful tool (Sappington, 1999)[3]. I

Fires. California's forest fires have been assessed using GIS in partnership with the USDA forest Region 5 Burned Area Emergency Rehabilitation (BAER) program (Brennan and Hardwick, 1999)[4] Risk analyses are used to determine the best and most cost-effective rehabilitation strategy (usually implemented within a week of the fire). The critical step in the BEAR program is the mapping of the burn *intensity* (the *impact* of the fire on the watershed and ecosystems) in it. The GIS data contains ground measurements for soil samples, ground cover and hydrophobicity of

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[2] K. Corbley, Radar Imagery Proves Valuable in Managing and Analyzing Floods, Earth Observation Magazine, Dec. 1999.
[3] N. Sappington, Mapping out a Plan for Disaster preparedness, Earth Observation Magazine, Dec. 1999.
[4] M. W. Brennan and P. E. Hardwick, Burned Area Emergency Rehabilitation Teams Utilize GIS and Remote Sensing, Earth Observation magazine, July/Aug. (1999).

the soil, as well as watershed boundaries, pre-fire vegetation and wildlife habitats. This data base is integrated through the GIS and can be used at different spatial scales, thus enabling rapid and accurate remediation as well as feedback for more long-term remediation and recovery planning.

Pacific Meridian and TASC teamed to combine their GIS capabilities in providing digital maps to BEAR, the maps were provided within 3 to 5 days of being called into operation, well with the 7 days window. The sensing system included an infrared digital camera (DCS460CIR) made by Kodak, an inertial measurement system and GPS, mounted on a small airplane. All of the information is stored in a GIS of geospatial data, including digital elevations.

Cooperation on Artic Pollution between US and Russia

An important outcome of the use of GIS has been the increased and open collaboration among the scientists involved in the assessments. The databases were maintained in two GIS systems.

In the context of the US/Russian Joint Commission on Economic and Technological Cooperation (the Gore-Chernomyrdyn Commission, GCC) the environment was a critical focus. Using classified reconnaissance techniques, the two sides could study environmental effects from oil spills and other hazardous activities. The main focus was the health risks posed by oil and gas, as well as the risk to forests in Arctic and Sub-Arctic systems, particularly fragile ecosystems (Mangis, 1999).

The US EPA risk methods were used to assess the risks and the data were collected remotely from both civil and (formerly) classified sensor systems. Those data were input into GIS. Remote sensing was critical to the information flow and display through GIS. The remote location of the Ob River, in Russia, made it vital to use airborne and space-based sensors, as well as oceanographic resources. The risk assessment included oil spill and sprays road construction (Slonecker, Jutro, Mangis, True, and Orlick, 1999)[5]. To assess those risks, environmental managers could see landscape, vegetation, pipeline construction and their routes, road construction and their routes, wind direction and speed, temperature and other critical parameters to the management of potential hazards. In the event of oil spill and sprays, information n the water, soil and ice composition can also be displayed on maps and thus, through relationships established via coordinate systems, identified and tracked in real time.

Data was developed from Advanced Very High Resolution Radiometer, operated by NOAA's satellites. Landsat's Multispectral Scanner and Thematic Mapper were a major component of the instrumentation to develop data for lake and wetlands productivity.

Remark

A common tread in disaster management programs, as the successful implementation of mitigation plans and their implementation, points to GIS as the basic and most useful tool (Sappington, 1999)[6].

The next Section includes a direct assessment of a number of case studies that are studied using a template. The purpose of this Section is to provide additional specificity to the narratives just given.

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[5] E. T. Slonecker, P. Jutro, D. Mangis, M. true and B. Orlick, Arctic At Risk, Earth Observation Magazine, 1999.

[6] N. Sappington, Mapping out a Plan for Disaster preparedness, Earth Observation magazine, Dec. 1999.

ADDITIONAL CASE STUDIES BASED ON ENVIRONMENTAL APPLICATIONS OF GIS: THE *TEMPLATE* APPROACH

The heterogeneity of information contained in the case studies reviewed under this work suggests that a uniform protocol for discussion. We have developed a common frame for analysis, a *basic template,* applied to each single study. The general template has been developed independently of the specific study. It is given next, with discussions of what is ideally relevant in the context of environmental work.

After the studies were selected the common template was used to summarize the content and quality of the information contained in each study. These templates follow the basic template. The information contained in each of the temples is diverse: different Authors report different aspects of their study. Nevertheless, we have found that, in the aggregate, the information provided support the findings discussed in the text.

The model template is provided next:

Model Template

Title: TEMPLATE TO BE USED FOR EACH APPLICATION OF GIS REVIEWED IN THIS REPORT AND A HYPOTHETICAL EXAMPLE FOR SITE XYZ

Mission statement as determined by user of results:

Develop a plan for site XYZ's decommissioning and closure by 2003.

Type of work (public, private) and availability of information:

Public, generally open with some limited non-disclosure agreements

User's Goals:

Minimize costs and environmental or other liability

User's Constraints (Financial, Personnel, other):

Sufficient financial backing and personnel.

GIS program and ownership:

ArcView

Risk Application:

- Ecological: yes, Uses EPA Methods and data
- Human health: yes Toxicological and epidemiological data; Uses EPA Methods and data where available.
- Financial: yes, uses NPDV for costs and benefits. All values are deterministic
- Other: liability heuristic analysis, supported by counsel's opinion.

Uses of GIS as the:

- Sole role: No
- Adjunct to other software and primacy of GIS use: coupled GIS with air and surface water outputs from dispersion/diffusion and chemical reactions of various types to describe and predict fate and transport of chemical agents over time and over the site and its boundaries.

4. Other roles: presenting 3-D description to management to justify clean-up alternatives and preferred option set for decommissioning.

Intended use: As per goals and objectives

Unintended uses: Adversarial stakeholders have criticized the accuracy of the projections.

Mode of Use in the Case Study:

- Compliance with regulations or laws: yes, CERCLA and its regulations
- Description of a situation: yes
- Prediction of future outcomes or events: yes, deterministic portrayal.
- Other modes of use: Internal operations of the site.

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): sources and concentrations of Pb, Cd, U235, Tetrazine. Site topography, water table depths, soil types. Vegetation, endangered species, niches. Human population data at the sites's fenceline from 1999 to 2020. Population income over the same periods
- Indirect variables; Education levels as a proxy for status
- Other: None

Models coupled with GIS:

Air: Gaussian plume with correction for elevations.

Water (surface): one-dimensional advection-diffusion model.

Water (groundwater, zone): Transient, unsaturated flow

Solid wastes. None

Demographic: Ricker's equation (density dependent growth rate) for endangered species; stochastic migration for population prediction

Economic: Taken from regional master plan predictions

Social: taken from regional master plan

Other: None

Uncertainty:

- Worst case or other scenario building: Yes but ad hoc and without considering overlaps among the choices nor the dominance of a choice over another via decision-theoretic methods.
- Probabilistic: partially, through demographic model
- Other: None.

Variability:

- Statistical: partial in the demographic model
- Other: none.

Communication of Risks:

- Stakeholders: not implemented but planned
- Consensus Building: yes, planned
- Other: None

Results from Uses as Described by Users or Developers:

The project is on going. Management is quite taken with the graphical displays and has been developing a warm and fuzzy feeling towards GIS and its potential. There is some skepticism about garbage in-garbage out.

Personal Comments on:

- Usefulness of analyses and assessment: Too early to develop
- Results achieved by users: too early to develop.

Lessons Learned: clarity of assumptions is critical to respond to management

Application of the Template to Real-World Studies:

EXAMPLE 1.

T. McCormick, GIS Is No Pipe Dream for Stormwater Systems, *American City and County*, pp. 59 - 70, May 1994.

Mission statement as determined by user of results: Meeting permit requirements under the NPDES efficiently

Type of work (public, private) and availability of information: public

User's Goals: The cost-effective and efficient compliance with NPDES storm water permitting requirements. Federal and local regulations constrain the goal-seeking activities.

User's Constraints: None stated.

GIS program and ownership: None specifically stated.

Risk Application:

- Ecological: Routine risks.
- Human health: contamination of water supply.
- Financial: Clean-up costs and tax revenues
- Other: None.

Uses of GIS: Sole role

Intended use: manage spatial and other NPDES data, integrate water model inputs and outputs, analytical support for management's decision-making

Unintended uses: None

Mode of Use in the Case Study:

- Compliance with regulations or laws: NPDES
- Description of a situation: yes
- Prediction of future outcomes or events: yes, deterministic portrayal.
- Other modes of use: None.

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): Storm run-off.
- Indirect variables: None

- Other: None

Models coupled with GIS: EPA's Hydrological Simulation Program (HSPF)

Uncertainty: None

Variability: None

Communication of Risks: None

Results from Uses as Described by Users or Developers: GIS is a cost-effective method for developing input information for management.

Comments: a useful way to track non-compliance, integrate and display information.

EXAMPLE 2

M. V. V. Kamaraju, A. Bhattacharya, G. S. Reddy, G. C. Rao, G. S. Murthy and T. C M. Rao, Ground Water Potential Evaluation of West Godavari District, Andhra Pradesh State, India - A GIS Approach, *Ground Water*, 34:318 - 325 (1996).

Mission statement as determined by user of results: To demonstrate the efficacy of the GIS in ground-water studies

Type of work (public, private) and availability of information: Public

User's Goals: evaluation of ground water prospects in a geographical area, as occurrence and distribution (ground-water potential map".

User's Constraints (Financial, Personnel, other): None stated

GIS program and ownership: ARC/Info.

Risk Application: Potential geological risks, vulnerability that can accompany the use of ground water.

Uses of GIS: Sole role.

Intended use: evaluate the soil, geomorphology structure and recharge conditions of the West Godovari District.

Unintended uses: None

Mode of Use in the Case Study: demonstration of GIS for describing potential ground-water uses.

Types of Factors or Variables Used in GIS:

- Direct variables: ground water.
- Indirect variables: lithology, geomorphology, structures, recharge conditions

- Other: None

Models coupled with GIS: None

Uncertainty:

- Probabilistic: qualitative.

- Other: None.

Variability:

- Other: GWPI and GWFI values

Communication of Risks:

- Stakeholders: anyone interested in the potential for ground-water uses.

Results from Uses as Described by Users or Developers: decision-maker benefited from the GIS displays from rapid retrieval of complex information and use of water for public consumption and agriculture.

Personal Comments on:

- Usefulness of analyses and assessment: very useful

- Results achieved by users: displays

- Lessons Learned: none stated

EXAMPLE 3

S. B. Lovejoy, J. G. Lee, T. O., Randhir, and B. A. Engel, Research Needs for Water Quality Management in the 21st Century: a decision support system, *J. Soil and Water Conservation*, 52: 18 – 22 91997).

Mission statement as determined by user of results: optimize the trade-off in a mix of services provided by enhanced water quality

User's Goals: maximization of watershed resources management through GIS use coupled to a wide variety of water supply and hydrological models.

User's Constraints: None stated or relevant; financial on uses of models

GIS program and ownership: GRASS (Geographical Resources Analysis System),

Risk Application Ecological, human health, and financial costs of run-off pollution from agricultural activities.

Uses of GIS: Adjunct to other software with primacy of GIS as the means to represent spatial information

Intended use: Managing resources according to economic criteria.

Unintended uses: None given

Mode of Use in the Case Study: Compliance with regulations or laws, description and prediction of future water management actions

Types of Factors or Variables Used in GIS

- Direct variables: water use.
- Indirect variables: agricultural run-off.

Models coupled with GIS

Water (surface): biophysical and distributed parameter hydrological simulations, as well as biological crop growth simulations.

Uncertainty: None

Variability: None

Communication of Risks: to public stakeholders

Results from Uses as Described by Users or Developers: fundamental enhancement of decision making with multiple and complex data and models

Personal Comments: None

EXAMPLE 4

A. I. El-Kadi, A. A. Oloufa, A. A. Eltahan, and H. U. Malik, Use of a GIS in Site-Specific Ground-Water Modeling, *Ground-Water*, 32: 617 - 625 (1994).

Mission statement as determined by user of results: facilitate ground-water modeling efforts by using data-handling and geographical capabilities of GIS, in Hawaii.

User's Goals: use GIS to facilitate site-specific ground-water modeling and their management.

User's Constraints:

GIS program and ownership: MapInfo

Risk Application: None.

Uses of GIS: Sole role or coupled to a USGS 2-D flow and transport model (MOC).

Intended use: Modeling using a GIS/modeling system

Unintended uses: None

Mode of Use in the Case Study: Description of a situation taken as an example.

Types of Factors or Variables Used in GIS:

- Direct variables: water
- Indirect variables: ground-water parameters

Models coupled with GIS:

Water (groundwater): USGS ground-water model (MOC).

Uncertainty

- Worst case or other scenario-building: none
- Probabilistic: none
- Other: finite difference numerical modeling

Variability: None discussed

Communication of Risks: None

Results from Uses as Described by Users or Developers

Personal Comments on:

- Usefulness of analyses and assessment: the fact that GIS includes a BASIC programming language facilitates coupling external models to the GIS environment.
- Results achieved by users: site-specific analyses were successfully conducted and indicate that the GIS-BASIC is very useful.

EXAMPLE 5

D. W. Watkins, D. C. McKinney, D. R. Maidment and M-D. Lin, Use of GIS in Ground Water Flow Modeling, *J. Water Res. Planning and Management*, 122:88 - 95 (1996).

Mission statement as determined by user of results: Evaluate the usefulness of GIS in regional ground-water modeling.

User's Goals: use GIS to facilitate site-specific ground-water modeling and simplifying the modeling. More accurate modeling lessens the potential for environmental errors. Case study of the High Plains aquifer in Texas.

User's Constraints: Inexperience in the coupling of GIS to ground water and relational databases.

GIS program and ownership: Unstated

Risk Application: None.

Uses of GIS: Sole role and as adjunct to other software. Different GIS (raster and vector) were compared.

Intended use: Show the effectiveness of GIS coupling to MODFLOW (a ground-water model)

Unintended uses: None

Mode of Use in the Case Study: Descriptions and comparisons of different GIS systems coupling to a relational data base accessed through the GIS SQL language capability. Also used the Rhode Island GIS.

Types of Factors or Variables Used in GIS:

- Direct variables: ground water flow.

- Indirect variables: none

Models coupled with GIS

Water (groundwater)

Uncertainty: None

Variability: None

Communication of Risks: None

Results from Uses as Described by Users or Developers

Personal Comments on:

- Usefulness of analyses and assessment

- Results achieved by users

Lessons Learned: The coupling was helpful but the time required to set up the coupling was longer than expected. This problem was in part due to the inexperience of the researchers. The GIS itself is limited in its ability to make complex calculations.

EXAMPLE 6

C. P. Baker, M. D. Bradley, and S. M. Kazcor Bobiak, Wellhead Protection Area Delineation: Linking Flow Model with GIS, *J. Water Res. Planning and Management,* 119: 275 - 287 (1993).

Mission statement as determined by user of results: Use maps created using GIS as the basis for local planning for protecting wells.

User's Goals: use GIS to facilitate site-specific ground-water protection.

User's Constraints: None

GIS program and ownership: ArcInfo and RIGIS (a state's GIS database at the University of Rhode Island).

Risk Application: Water quality protection and clean-up costs.

Uses of GIS: Sole role and as adjunct to other software for modeling ground-water (based on the uniform flow equation).

Intended use: Show the effectiveness of GIS to map areas that feed the wells and assist in the protection of those areas by coupling of the ground water model to the GIS.

Unintended uses: None

Mode of Use in the Case Study: Descriptions

Types of Factors or Variables Used in GIS:

- Direct variables: ground water
- Indirect variables: interferences with ground-water flow to wells

Models coupled with GIS: Uniform Flow Equation and other ground water models.

Water (groundwater).

Uncertainty: None

Variability: None

Communication of Risks: Local government, water utilities and consumers.

Results from Uses as Described by Users or Developers

Personal Comments on:

- Usefulness of analyses and assessment: the coupled models have been demonstrated to be valuable in the protection of the state's wells.
- Results achieved by users: successful demonstration of the coupling and usefulness to the public stakeholders.

EXAMPLE 7

S. T. Taher, J. Labadie, Optimal Design of Water Distribution Networks with GIS, *J. Water Res. Planning and Management*, 122: 301 – 311 (1996).

Mission statement as determined by user of results: Construct a compute-aided support tool for water resources engineers, applied to Greeley, Colorado.

User's Goals: use GIS to facilitate engineering work

User's Constraints : Typical water distribution physical and financial constraints.

GIS program and ownership: ARC/Info, ARC/View, ARCEDIT, ARCSHELL.

Risk Application: Water quality simulations.

Uses of GIS: GIS, with input to optimization of water resources planning and management by non-linear programming and network solver (WADSOP).

Intended use: Show the effectiveness of GIS to get optimal design of water-distribution networks.

Unintended uses: None

Mode of Use in the Case Study: Descriptions and comparisons of models results through deterministic simulation

Types of Factors or Variables Used in GIS:

- Direct variables: water
- Indirect variables: financial constraints on the optimization processes

Models coupled with GIS: AutoCad, WADSOP

Uncertainty: None

Variability: None

Communication of Risks: None.

Results from Uses as Described by Users or Developers: The GIS was deemed a very powerful adjunct to the decision making process

Personal Comments on: None

Usefulness of analyses and assessment: An essential tool

Results achieved by users: Multiple simulations and examples showed the usefulness of coupling to GIS physical flow models.

EXAMPLE 8

C. Shea, W. Grayman, D. darde, R. M. Males, and P. Sushinsky, Integrated GIS and Hydrological Modeling for Countywide Drainage Study, *J. Water Res. Planning and Management,* 119: 112 - 127 (1993).

Mission statement as determined by user of results: Develop a surface water management plan for a large area, Polk County, FA

Type of work (public, private) and availability of information: public drainage planning and management

User's Goals: Planning a drainage system for the County.

User's Constraints: None stated.

GIS program and ownership: AEGIS (Aeronca's Electronics geographic information system) which is a raster-based system

Risk Application:

- Ecological: Routine risks.
- Human Health: contamination of water supply.
- Financial: Clean-up costs and tax revenues
- Other: Damage to water supply system.

Uses of GIS: integrating system using R:data base management system, HEC-1 and HEC-2 (hydrological (hydrograph) models); AUTOCAD.

Intended use: develop a management plan for surface water

Unintended uses: None

Mode of Use in the Case Study:

- Compliance with regulations or laws: yes
- Description of a situation: yes
- Prediction of future outcomes or events: deterministic.
- Other modes of use: protection through proper planning.

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): Surface water.
- Indirect variables: Human developments
- Other: None

Models coupled with GIS: CAD

Uncertainty: None

Variability: None

Communication of Risks: None

Results from Uses as Described by Users or Developers: The integration of the models in a GIS made possible the study of a large set of management alternatives.

Comments: The entire process took about 4 years because there had been no experience with the integration of diverse systems and data. The newer GIS would allow that development to take much less time and be user-friendlier.

EXAMPLE 9

H. S. Rifai, C. J. Newell, and P. B. Bedient, Getting to the Nonpoint Source with GIS, *Civil Engineering*, 3: 44 - 46 (1993).

Mission statement as determined by user of results: Enhancing map-based computations for non-source pollution

Type of work (public, private) and availability of information: public, Galveston Bay, TX

User's Goals: Characterizing the source of non-point pollution in a large area.

User's Constraints: None stated.

GIS program and ownership: ARC/Info.

Risk Application:

- Ecological: Routine risks.
- Human Health: contamination of water supply.
- Financial: Clean-up costs and tax revenues
- Other: None.

Uses of GIS: integration of CAD, Data Base and GIS.

Intended use: develop a management plan for surface water quality and quantity

Unintended uses: None

Mode of Use in the Case Study:

- Compliance with regulations or laws: No
- Description of a situation: yes
- Prediction of future outcomes or events: No.
- Other modes of use: None

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): Several surface water contaminants.

- Indirect variables: Non-point sources
- Other: None

Models coupled with GIS: Surface water hydrological model and various data from satellites and other sources

Uncertainty: None

Variability: None

Communication of Risks: Public, local municipalities

Results from Uses as Described by Users or Developers: particularly helpful to the management of non-point source of water pollution.

Comments: None

EXAMPLE 10

D. C. McKinney, D. R Maidment, and M. Tanriverdi, Expert Geographic Information System for Texas Water Planning, *J. Water Res. Planning and Management*, 119: 170 – 183 (1993).

Mission statement as determined by user of results: Feasibility of using Expert GIS for long-term regional water resources planning in Corpus Christi, TX

Type of work (public, private) and availability of information: public,

User's Goals: Planning over a 50-year time horizon the potential sources of water for supply for the area of study.

User's Constraints: None stated.

GIS program and ownership: GIS (type not mentioned).

Risk Application: None.

Uses of GIS: integration of CAD, Data Base and GIS based on artificial intelligence (rule-based expert systems) interface, as well as water supply modeling.

Intended use: water resources planning

Unintended uses: None

Mode of Use in the Case Study:

- Compliance with regulations or laws: Yes
- Description of a situation: yes
- Prediction of future outcomes or events: Yes (water shortages).
- Other modes of use: None

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): Surface water and ground water sources.
- Indirect variables: None
- Other: None

Models coupled with GIS: Water supply distributions models, Expert System,

Uncertainty: None

Variability: None

Communication of Risks: Public, local municipalities

Results from Uses as Described by Users or Developers: Automated displays of complex information and optimal decision-making based on least cost algorithm. The interface between the models allows changes to one model without affecting the other, enhancing applicability and reducing downtime.

Comments: Complex system require large amounts of computing time, as well as fast numerical processor and optimized numerical sub-routines.

EXAMPLE 11

M. Pearson and S. Wheaton, GIS and Stormwater Management, *Civil Engineering*, 63:72 - 73 (1993).

Mission statement as determined by user of results: Feasibility of using GIS for economical management under the NPDES

Type of work (public, private) and availability of information: public, Anchorage, Alaska

User's Goals: Meet the NPDES

User's Constraints: resources to implement and use GIS

GIS program and ownership: ARC/Info.

Risk Application: None.

Uses of GIS: Storm water management tool of choice

Intended use: water resources planning

Unintended uses: None

Mode of Use in the Case Study:

- Compliance with regulations or laws: Yes
- Description of a situation: yes
- Prediction of future outcomes or events: No.
- Other modes of use: None

Types of Factors or Variables Used in GIS:

- Indeces (e. .g, linear combinations of factors or variables): None
- Direct variables (e. g., air pollution concentrations): Storm water.
- Indirect variables: None
- Other: None

Models coupled with GIS: None

Uncertainty: None

Variability: None

Communication of Risks: Public, local municipalities, US EPA

Results from Uses as Described by Users or Developers: Critical in permit application and in the development of storm water monitoring activities by the City. Overall, the GIS allow the merger of different types of planning expertise (physical, demographic and so on) and is successful at doing so.

Comments: The GIS system should be off-the-shelf to minimize the time to becoming familiar with it; moreover, if the system is in widespread use, the labor required to use it can be readily found.

CONCLUSIONS

This work shows that GIS is an extremely useful means for collecting, storing and mapping heterogeneous environmental information. GIS can serve as an integrative system for inputs from different fate, transport and risk models and to display such integrated information for further analysis and for input into management to inform their choices. In the context of environmental work, it can also help to reduce uncertainty in making risky decisions and, as Meta-GIS, can go well beyond the traditional uses of GIS alone and its uses in problem solving. The critical conclusion is that Meta-GIS, as described in this paper, yields a set of robust tools that can be included in environmental work's toolbox, thus enhancing its use and success. The common goals of risk analysis and management require modeling the fate, transport and uptake of noxious chemicals, their adverse effects through dose-response models and how to intervene to mitigate or prevent hazardous outcomes. However, the differences in the characteristic of the sites for which the USAF is responsible make each risk analysis unique: this paper suggests that those difficulties can be addressed, in the context of environmental work, by Meta-GIS, as shown by the real-world cases illustrated via the applications of the basic template.

Using GIS, as the case studies demonstrate in quite different contexts and applications, provides great flexibility for both analysis and for management by enhancing the understanding of complex risk situations and uncertain environmental outcomes. The template of case studies developed in this work can be used in support of site-specific analyses and can also serve as a guide in understanding an often-complex literature. The template can also be used interactively in management to understand spatial and temporal risk profiles and, at the same time, allow risk analysts to better understand complicated relationships between heterogeneous inputs through visual representations and the changes in those relationships through sensitivity or other types of uncertainty analysis.

Further research can be directed to study how Meta-GIS can help in dealing with overlapping uncertainty and variability bounds, such as when stochastic dominance does not permit a clear cut choice among two or more alternative choices.

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