GIS Modeling of Significant Karst Areas for Purchase and Protection

George Veni
George Veni and Associates

Joe Chapa
Information Services Department, City of San Antonio

Geary Schindel
Edwards Aquifer Authority

Kirk Nixon
San Antonio Water System

Dan Stone
ESRI

Abstract

In May 2000, the voters of San Antonio, Texas, approved a sales tax increase to raise $65 million over four years to purchase land over the recharge zone of the karstic Edwards Aquifer and local streams. A team of karst, hydrogeology, wildlife, GIS, and land management specialists was assembled to develop a strategy for identifying properties with highest hydrologic and aquifer protection value for possible acquisition. GIS methods were determined the most effective means of assessing the properties. A GIS model was constructed of three components: vulnerability, watershed, and biology. Each component comprised spatial data layers weighed according to their significance. Vulnerability layers were land slope, faults, caves, sinkholes, and the permeability of the geologic units. Watershed layers were property size, properties adjacent to existing preserved or protected areas, and areas that drain into known caves. Biology layers were the distribution of federally listed endangered bird and karst invertebrate species. The three components were respectively weighted at 50%, 30%, and 20% and combined. Sensitivity testing was conducted to assure the optimal quality of the model's output, which was presented in three tiers of priority for acquisition based on the numerical values for the properties. The results were provided to land agents working for the city who checked the availability of the highest tier properties first. To date, approximately 11 square kilometers have been purchased and are creating what may prove an important buffer to mitigate impacts from the extensive urbanization occurring on the Edwards Aquifer recharge zone.

Introduction

The San Antonio Segment of the karstic Edwards (Balcones Fault Zone) Aquifer (hereafter called Edwards Aquifer) is the primary water supply for the City of San Antonio and approximately 1.5 million people. The aquifer has been the subject of intense political and public debates on the management of its water quantity and quality. The growing population and demand for aquifer water in the region has led to efforts to increase the volume of recharge entering the aquifer, such as the construction of recharge enhancement structures (for example, Bader, Walthour, and Waugh, 1993). However, some of this growth and its urban development have been on the recharge zone, where water enters the aquifer, and has prompted concern about potential groundwater contamination and recharge reduction (for example, Kipp, Farrington, and Albach, 1993).

On May 6, 2000, the citizens of San Antonio voted to approve the ballot item listed as "Proposition 3," a ⅛-cent sales tax to raise $65 million over four years for the purchase of environmentally sensitive lands within the city's limits and extra territorial jurisdiction within Bexar County. $20 million was allocated for the creation of linear parks along Leon and Salado creeks. $45 million was allocated for the purchase and management of land over sensitive zones of the Edwards Aquifer. The purpose of the land purchases is to reduce adverse impacts on surface and groundwater quality by preserving critical, undeveloped lands to maintain natural, uncontaminated flows into the aquifer and creeks. Given the land values at the time of the vote, an estimated 40 square kilometers of Edwards Aquifer land were hoped to be purchased. This paper describes the process used by the City of San Antonio to identify the tracts of land that would be most favorable to purchase for aquifer protection.

To accomplish this task, the City organized a Scientific Evaluation Team to provide scientifically based information that will assist in the identification of properties for possible acquisition. The Team comprised scientists and managers expert in the hydrogeology and karst of the Edwards Aquifer, threatened and endangered species in the region, wildlife habitat management, and in the City's administrative processes. They represented the following agencies and organizations:

- City of San Antonio Public Works Department
- City of San Antonio Parks and Recreation Department
- Edwards Aquifer Authority
- George Veni and Associates
- San Antonio River Authority
- San Antonio Water System
- Texas Parks and Wildlife Department
- U.S. Geological Survey (USGS)
- U.S. Natural Resource Conservation Service
- University of Texas at San Antonio

Approximately 2,000 volunteer manhours were spent by the members of the Team, who donated their time and services to the City.

Methodology

During the first meeting of the Scientific Evaluation Team, it became quickly apparent that the most effective means of analyzing the complex and multiple data sets for this process would be through Geographic Information System (GIS) modeling. All of the data were spatial or could be spatially represented in an ordered series of layers that could be combined for analysis and decision making. The spatial representation was technically effective but also offered a clear and intuitively understandable process for the general public to see that their tax dollars were well spent. ArcView Spatial Analyst and Model Builder were selected as the software to process the data. ESRI, Inc., ArcView's producer, provided substantial volunteer support to facilitate construction and processing of the GIS model.

The Scientific Evaluation Team identified three primary scientific layers of spatial data for the GIS model: geologic, biological, and watershed. Each layer was composed of sublayers, spatial data that were assigned point values and combined to give an overall value to the primary layer for a given location. Data for the layers and sublayers were derived from several sources and at different scale resolutions. Much of the data were originally established as 30-square-meter blocks to match the resolution of the digital elevation data for the area (Clark, 2000). All spatial data were subdivided to a common scale of one-square-meter areas to allow uniform and proper overlay of the data. Following is a discussion of the data entered into the model and how they were analyzed.

Geologic data layer

The foundation for this layer was an Edwards Aquifer groundwater vulnerability map prepared by the U.S. Geological Survey (Clark, 2000). In cooperation with Clark and other members of the U.S. Geological Survey, that map was modified for the GIS model by adjusting values based on new information and expanding it north into the aquifer's contributing zone (also called the drainage zone or catchment zone) to the county line (the legal limit authorized by Proposition 3 for purchasing properties). Sublayers used in the development of this geologic layer were land slope, faults, caves and sinkholes, and the permeability of the exposed geologic units. Soils were also used by Clark (1999) but not included in this model because they are locally thin to nonexistent, often patchy, and due to their similarity they would likely have little overall impact on the model.

Land slope relates directly to groundwater recharge. Areas of higher slope have a greater propensity for runoff than recharge. Veni (1997) found that recharge-formed caves are more likely to occur along streambeds or interstream uplands that have slopes of less than 5%. A digital elevation model for the county was analyzed, and areas were subdivided and assigned point values according to Table 1, with higher ratings reflecting greater potential for groundwater recharge.

Table 1: Recharge potential ratings for land slopes

Slope	Rating
Greater than 18%	1
Greater than 12% and less than 18%	3
Greater than 6% and less than 12%	5
Greater than 2% and less than 6%	9
Less than or equal to 2%	10

Mapped faults within the study area were added to the model. Their locations were imported from existing U.S. Geological Survey digital maps. The Scientific Evaluation Team recognized that many of the faults were not single isolated fractures but zones of fractures and drew the faults as 50-meter-wide areas in the GIS model. The width was selected based on field experience to include the zone where most fault-associated fractures were likely to occur. Since the full lengths of the faults were not precisely mapped in the field but interpreted from air photos and topographic maps, the 50-meter-wide fault areas are more likely to include the faults and most significant associated fractures where minor deviations from the mapped fault traces might occur. Fault areas were assigned the highest value of 35 points in the GIS model due to their potentially high permeability.

Caves and sinkholes are features of highest permeability and were also given the highest 35-point value in the GIS model. These features were defined in the model as 100-meter-diameter circular areas, which roughly approximate the horizontal extent of most local caves above the water table and capture most associated sinkholes and solutionally enlarged fractures. Satellite recharge features often form around caves and sinkholes in response to high permeability gradients (Kemmerly, 1982). The 100-meter-areas also comply with the 100 to 150-meter-areas used by the U.S. Fish and Wildlife Service to establish critical zones for the protection of caves in the area with federally listed endangered invertebrate species (USFWS, 2000a). Few sinkholes were included in the model because most are locally small, low relief features, and few appear on the 7.5-minute topographic maps of the study area.

The caves included in the model were those known to the U.S. Geological Survey. The Texas Speleological Survey was contacted for additional cave locations; but instead of specific locations, Texas Speleological Survey provided cave zones reflecting areas where one or more caves are known to occur. The zones were delineated based on geology, specific cave and karst feature locations not released to the model, security of the cave locations, and the extent of the caves. In general, larger zones suggest more known caves and karst features, and/or better understanding of the geology that gives confidence to extend the borders further to where caves have a high probability of existence. Since parts of these zones may not contain caves, they were given 30 points in the model, slightly less than maximum assignable value. Where known cave locations overlapped these zones, the higher 35-point value was used. Zone boundaries drawn along limestone quarries extended to the quarry walls as shown on the topographic maps. Some of the walls were probably excavated into the cave zones since the topographic maps were published. Cave zones were not drawn within existing parks or military bases since those areas are already preserved and/or unavailable for acquisition, although some zones were drawn outward from those boundaries.

The Scientific Evaluation Team recognized that significant recharge into karst aquifers occurs throughout the outcrop and not solely through features such as fractures, caves, and sinkholes. In order to model this recharge, the U.S. Geological Survey mapping of the study area's lithology was added to the model. This comprised mapping by Stein and Ozuna (1995) for the Edwards Aquifer recharge zone and by Clark (in review), which is the basis for recent, currently unpublished mapping of the aquifer's contributing zone. Inclusion of the contributing zone was considered important because, though not yet formally designated as part of the recharge zone by the State of Texas, significant recharge into the Edwards is known to occur in this area (Veni, 1995).

Five stratigraphic formations occur in the study area and have been mapped as 15 different lithologic units. These were grouped into four categories according to their mean permeability, which is highly affected by their degree of karstification. The most permeable units were assigned higher point values, the confining units received the fewest points, and the remaining two categories of units were assigned low and moderate values as appropriate.

Biological data layer

This layer is composed of data related to the distribution of federally listed endangered species. The species fall into two groups: karst invertebrates and birds. Maps developed through the U.S. Fish and Wildlife Service (Veni and Associates, 1994) were used in the model to delineate the areas known to be occupied by the karst invertebrates or the varying potential for their presence as rated in Table 2. These maps were updated to include the most recent available information on the species' distribution. Highest point values were given to known endangered species zones, no points were given to zones that do not contain the species, and low to moderate values were assigned as appropriate to the intermediate zones. At the time the model was constructed, the karst invertebrates were proposed for endangered listing (Rappaport, 1998) and were listed by the end of the year (USFWS, 2000b). Since some endemic invertebrates in the area are rarer than some of the listed species, the zones also consider the probability of those animals being present should they ever be listed.

Table 2: Classification of karst invertebrate zones

Zone	Classification
Zone 1	Contains endangered cave species
Zone 2	High probability of endangered or endemic cave species
Zone 3	Low probability of endangered or endemic cave species
Zone 4	Requires further study
Zone 5	Does not contain endangered cave species

Maps showing the distribution of the endangered bird species were unavailable, but USFWS provided vegetation maps of the county from which potential bird habitat could be deduced, as described by Campbell (1995). The areas were classified as:

- water
- ashe juniper or mixed ashe juniper oak forest
- ashe juniper or mixed ashe juniper or mainly deciduous forest
- ashe juniper or mixed ashe juniper oak woodland
- ashe juniper or mixed or mainly oak savanna
- grassland
- urban vegetated
- barren, sparsely vegetated
- no data (outside the study area)

To relate these areas to endangered bird species, the Scientific Evaluation Team reclassified them with diminishing point values as:

- potential endangered species habitat
- grassland
- water, barren, urban
- no data (outside the study area)

Since endangered bird habitat was not definitively delineated by this mapping, its highest point value was set equal to Zone 2 for the karst invertebrates.

Watershed data layer

The geologic data layer identifies important recharge features such as caves. However, the Scientific Evaluation Team recognized that protection of recharge water quality and quantity requires the preservation of watersheds. Maps of only large watershed boundaries were available and were not at a scale useful to the GIS modeling. Digitizing smaller watersheds in the county was beyond the scope of the Scientific Evaluation Team, so property size and connectivity were combined for use as watershed surrogates.

Undeveloped properties greater than 242,820 square meters (60 acres) in size were valued higher in the model than smaller properties. This factor was determined from the fact that generally larger properties will encompass larger portions of watersheds. Undeveloped land allows unimpeded and uncontaminated recharge and also buffers the adverse impacts of surrounding developed land by dilution. Schuleler (1994) summarized the results of multiple studies on the relationship between impervious cover and streams. He found that watersheds with more than 10% to 20% impervious cover suffered significant degradation in water quality, biodiversity, stream temperature, and stability of stream channel shape and position. However, since there was no specific size area that had been demonstrated as critical to maintaining groundwater quality, the 242,820-square-meter area was selected as the minimum size for its effectiveness in managing and preserving wildlife habitat (Adams, 1994). This area also approximates the minimum size of the endangered karst species preserves per the protocols of the U.S. Fish and Wildlife Service (2000a). Property boundaries and attributes such as size and land use were provided for the model by the Bexar Appraisal District.

In order to capture larger portions of watersheds, property connectivity was added as a sublayer to the model. This element gave high point values to properties that are adjacent to existing preserved or protected areas (parks, flood control dam reservoirs, and military installations). Adjacency was determined as undeveloped properties within 60 meters of the preserved or protected properties to account for streets and slightly mis-matched boundaries drawn from different mapping sources.

Within the watershed layer of the GIS model, value was also given to areas that drained into known caves and could be mapped at the scale of the 7.5-minute topographic maps. Drainage areas for caves located in the beds of large creeks were drawn to encompass the parts of the watershed nearest those caves that, based on field experience, would likely contribute runoff into the caves. The upper reaches of such watersheds were excluded since much of that water recharges the aquifer before reaching those caves. Also, there is less need to protect those areas, relative to the caves, since any contaminants in their runoff would be significantly diluted during large storms where upstream flows extend to the caves.

Processing the GIS Model

ArcView Model Builder was used to process the data for the GIS model. Point values for the sublayers of each square meter of the study area were summed to generate the value of those areas for the primary geologic, biological, and watershed layers. Rather than simply summing the primary layers, they were first weighted according to importance and then summed to produce the model's map of the area. The geology layer was weighed as 50%, the biology layer as 20%, and the watershed layer as 30%. While protection of endangered species is important, biology was not given greater weight since the purpose of Proposition 3 was the protection of Edwards Aquifer groundwater. The biology was used to identify hydrologically important lands that were also ecologically important. The points and weighting of the layers were tested with different values to determine which numbers gave results that appeared the most technically accurate. Figures showing the model's output map and its component layers are not presented with this paper. These maps require color reproduction, unavailable for these proceedings, to be understood.

Results, Interpretation, and Use of the Model

The GIS model calculated total scores from the layers and output a point ranking for each square meter of the study area. These areas were divided into eight categories and color-coded for visual display. The six highest categories were recommended by the Scientific Evaluation Team for consideration for acquisition; the two lowest categories may not have sufficient hydrogeologic and biological qualities to warrant their acquisition unless all higher scoring properties have been exhausted. The six categories were grouped by twos to create three tiers to simplify targeting properties for potential acquisition. Tier 1 contains the highest point-scoring areas and was recommended for first examination for acquisition. The model easily highlights the tiers as groups and can list the target properties by size, value, owner, or other desired attributes.

Although the model provides a simple and effective means of identifying hydrologically and ecologically important properties, the Scientific Evaluation Team offered several comments to the Conservation Advisory Board, which reviewed the properties for acquisition by the city. These comments explained how the model was developed, its limitations, and how it can be enhanced and better used.

One important factor in understanding the model's output is that the nature of the model required subdividing the aquifer area into several ranks. However, the nature of the aquifer is that all aquifer recharge and contributing areas are important to protect. The purpose of the model is to distinguish between small differences to facilitate the most effective purchases. Areas that rank low in the model should not be misconstrued as unimportant to the aquifer or not vulnerable to contamination.

The GIS model is dynamic. The Scientific Evaluation Team recommended that the model should be updated and run again as each new property is acquired or as protected properties are established in the area by other organizations. Connectivity of watersheds and habitat is an important factor in the model, so the establishment of new protected areas will generate new high priority areas to target for acquisition.

Several additional mapable features can be overlain on the model and should be considered in the decision making process. Weighing the importance of these features was considered a management decision and outside the scope of the Scientific Evaluation Team. Following is a list of some features and recommendations in their consideration.

- Census data: This information can be used to determine areas of growth and where land acquisitions may preferentially encourage or discourage growth in a manner that supports protection of the Edwards Aquifer.
- Golf courses: Hydrologically, these areas may produce poor quality runoff and should not be considered for hydrologic connectivity. However, some may provide biological

connectivity and should be considered if connectivity for endangered bird species is needed or available.

- Hazardous materials sites: These sites include but are not limited to landfills, quarries, leaking and non-leaking underground storage facilities, sewage lift stations, and sewer lines. Where a property has sufficient undeveloped land, it could be strategically used to ameliorate the impacts of such sites on that property or surrounding properties. These properties will need case-by-case evaluation to determine if they are worth purchasing. "Sufficient undeveloped land" will need to be determined case-by-case by the degree of known or potential impacts and the property's size and ability to significantly ameliorate the impacts. Only properties that are large enough to significantly ameliorate the impacts, or where the impacts are small enough to allow significant amelioration by the property's size, should be considered for acquisition.
- Development Plans: Existing development plans should be among the first factors evaluated in targeting properties for acquisition. The occurrence of such plans does not mean that a property should not be considered for acquisition. While some properties are far enough along in the development process to make them financially unavailable or hydrologically and/or biologically undesirable for acquisition, others may be viable and attractive for purchase. Additionally, acquisition of these properties may be strategically useful to discourage growth in certain areas and/or buffer the impacts of adjacent developments.
- Property improvement values: Undeveloped properties were identified for the model by including only properties with no added improvement value. However, a property may still be attractive for acquisition if it is largely undeveloped. The model can be run with a filter to identify low-value improvements, so that properties with only an old ranch house or similar structures might be included. High values can be used as a filter to try and locate properties with small strips of intensive development but otherwise undeveloped. However, these will require considerable effort to distinguish them from predominantly developed properties.

Properties primarily within 100-year floodplains should receive less priority for acquisition.

Those lands are generally undevelopable and, in the San Antonio area, existing regulations will preserve them as recharge sites. Efforts should focus on developable lands to protect the quality and quantity of water entering the floodplains and the aquifer.

Properties less than 242,820 square meters in size but adjacent to an existing preserve property should be given consideration equal to those properties greater than 242,820 square metes in size if they contain important hydrologic or biological features.

The model ranks properties based on their highest scoring square meter area. In some cases a small part of a property may rank the entire property higher than generally warranted. Any property considered for acquisition should first be reviewed on the output map of the GIS model that shows the point and not tier values to determine if the tier rank is representative of the property. It may be appropriate to negotiate acquisition for only the high-scoring part of a property, although in such a situation, as much of the undeveloped watershed as possible for that area should be included.

In some cases, a property may receive a high priority ranking based on the existence of endangered species habitat or a cave. Since those features are marked by areas that include buffer zones, the actual features of concern could instead be on an adjacent property. If a property is ranked highly by such a feature near its edge, the occurrence of the feature on the property should first be confirmed.

Conclusions

The GIS modeling of the karstic Edwards Aquifer area has proven a valuable and flexible tool in sorting through several complex factors involving a tremendous volume of information to identify properties that offer highest value for acquisition in the protection of the aquifer and its associated resources. As of the date this paper was presented at the National Cave and Karst Management Symposium, approximately 11 square kilometers were purchased with the Proposition 3 funding. Probably about 70% of the original 40 square kilometers acquisition goal will be met due to subsequent increases in land prices, but the citizens of San Antonio are satisfied with the efforts and are pressuring City Hall for another land bond election with even greater funding.

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