THE EFFECTS OF URBAN DEVELOPMENT ON RECHARGE OF THE EDWARDS AQUIFER IN SAN ANTONIO/BEXAR COUNTY, TEXAS

THESIS

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Acknowledgments

Thanks be to God for blessing me with the gifts of knowledge, patience, and persistence. "Your talent is your gift from God. What you do with that talent is your gift back to God."

To my family for all the sacrifices they have made to give me the best of everything. Thank you for always taking time out to read with me, for teaching me to question why things are the way they are, and for encouraging me to explore the world that we live in.

To my friends who have helped me keep my sanity during my educational career, thanks for reminding me that all work and no play make a pretty dull Dina.

To Karen McGilloway, Brother Frank Snider, Nicholas Bystrom, and Richard Earl, may I one day inspire others the way that you have inspired me.

To Wilfredo Ramirez who thinks that I am most beautiful when I am sitting on the couch in a tee shirt and wind-pants, hair clipped up, glasses on, and reading. Thanks for loving me when it wasn't easy.

"...There is one great truth on this planet: whoever you are, or whatever it is that you do, when you really want something its because that desire originated in the soul of the universe. It's your mission on earth. And when you want something, the whole world conspires in helping you achieve it."

Paulo Coleho

In loving memory of Nicholas Bystrom.

TABLE OF CONTENTS

FIGURES

TABLES

CHAPTER 1

THE PROBLEM AND ITS SETTING

Introduction

Water is essential for human life, agricultural and industrial production, and for water based recreation and transportation. It is central to many national concerns including energy, food production, environmental quality and regional economic development. Water is so much a part of our lives that it is often taken for granted even though it is unequally distributed in time and space causing problems of excess or scarcity. In most groundwater systems, replenishment and discharge are not uniform, the hydrogeology is not homogeneous, and pumping stresses are unevenly distributed. This may be best exemplified by the relationship between the Edwards Aquifer and the demands placed on it by the City of San Antonio, the aquifer's largest user. The city has been faced with protecting recharge, both quantity and quality, and lessening its dependence on the precarious and vulnerable aquifer.

The Edwards Aquifer is a unique groundwater system that is one of the most prolific artesian aquifers in the world. It serves the diverse agricultural, industrial, recreational, and domestic needs of over one million users in south-central Texas and is the primary source of water for San Antonio, the ninth largest city in the United States. As shown in Figure 1, the Edwards Aquifer is, in actuality, three hydrologically distinct

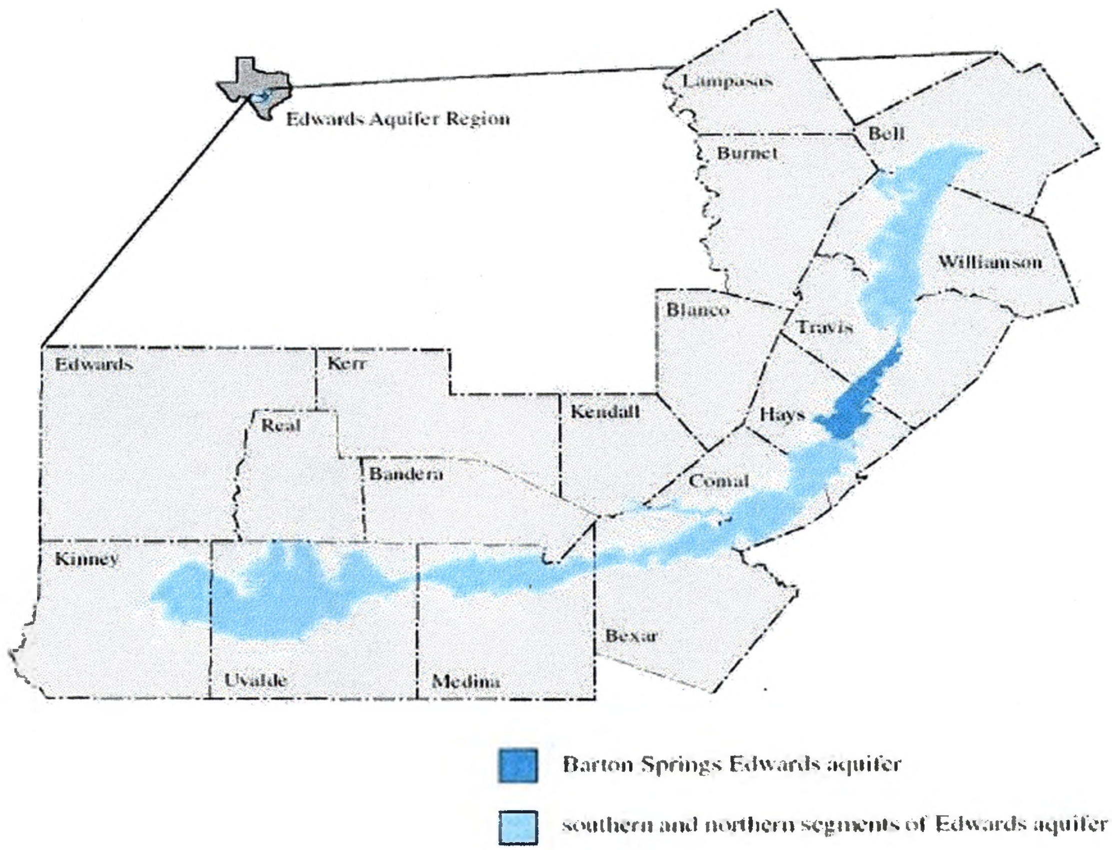

Fig. 1. Three Segments of the Edwards Aquifer.
Source: Barton Springs/Edwards Aquifer Authority Conservation District

aquifers: the north, the central Barton Springs segment near Austin, and the southern or San Antonio section (Texas Water Development Board 1997).

Despite the fact that only approximately 8 percent of the Edwards Aquifer recharge zone lies in the San Antonio/Bexar County region, the San Antonio section is where most of the major natural springs occur, where there are the greatest demands on the aquifer, and where water management issues are most hotly debated. In the coming decades, demand for water will increase beyond the aquifer's capacity to provide. San Antonio's population is growing steadily, and all indications are that it will continue to grow. According to *Water for Texas* (Texas Water Development Board 1997), San Antonio, located in one of the fastest growing regions in the state, has a 2050 projected population of 2,400,000 which is more than double the 1990 population of 1,065,000.

The population figures for the San Antonio area track a national trend during the 1990's of rapid growth in rural areas surrounding metropolitan areas (Anderson 1990, Williams 1996). Almost all of Bexar County's population growth over the past 25 years has been toward the north of the city and has been steered by politics, topography, technology, economics, and education. According to the San Antonio Planning Department, the northern sector's population has grown five-fold since 1970 from about 108,000 to nearly 553,000 in 1995. It had about 13 percent of the county's total population of 830,460 in 1970 but had nearly 43 percent of a 1995 population estimated at nearly 1.3 million.

Research Questions

It is evident that the population of the San Antonio/Bexar County area will continue to grow over time and that major decisions will have to be made to protect and manage the water resources of the area. The concepts of traditional growth and environmental integrity are in conflict with each other, yet there is a role for both. The purpose of this study is to examine development over the Edwards Aquifer recharge zone in the San Antonio/Bexar County area during the period 1970-2000 to determine what relationship, if any, exists between increased development and recharge of the Edwards Aquifer. Specifically, the following issues will be analyzed:

1) How has the change in land use affected the amount of impervious cover in the recharge zone of the Edwards Aquifer in the San Antonio/Bexar County area?
2) How has the change in impervious cover affected runoff and stream flow in the recharge zone of the Edwards Aquifer in the San Antonio/Bexar County area?
3) What effects do changes in levels of impervious cover, runoff and stream flow have on recharge amounts to the Edwards Aquifer?

This research will help to clarify the relative roles of direct aquifer recharge from the soil (in-situ recharge) versus stream channel transmission losses in the aquifer recharge process. Presently, the U.S. Geological Survey estimates that in-situ recharge is approximately twenty percent of total recharge (Slade 1984; Sharp and Banner 2000). Increased impervious cover is expected to decrease in-situ soil infiltration and increase flood flow, which would increase stream channel recharge.

CHAPTER 2

LITERATURE REVIEW

Containing many of the fastest growing metropolitan areas, the Southwest has grown faster than the nation as a whole (Sherldan 1981; Brown and Kane 1994; Gunter and Oelschlaeger 1997). Many factors have played a part in the Southwest's growth, including excessive groundwater pumping (Gardner 1995, Leopold 1997), the damming of the region's rivers (Leopold 1997; Donahue and Johnston 1998), and the transporting of water over long distances (Postel 1992; Cohen 1995). Billions of dollars have been spent developing water supplies, controlling floods, and cleaning polluted water, all in an effort to manage and develop water resources (Bedient et.al. 1994; Beekman 1998).

The farms, industries, and cities in the Southwest are straining the region's life support systems of water, soil, vegetation and clean air (Pimentel et. al. 1997; Postel 1999). Federal government subsidies have been linked to the exploitation of arid and semi-arid land resources resulting in the encouragement of production, not conservation (Postel 1986; Gardner 1995). Population growth and rising consumption patterns have reduced the amount of water available to each person. Water management, therefore, has focused on meeting needs by increasing the supply of available water. Human ingenuity has stretched the capacity of natural resources through technology, (Postel 1986; Goodland et. al. 1992; Campbell 1995) although it is not without its problems. One difficulty is that structural, high technology solutions are capital and energy intensive at a time when capital and energy are very expensive (Peet 1992; Beekman 1998). Another difficulty is that people who live in the basins from which the water is to be taken are becoming increasingly reluctant to give it up (Harper 1996; Gunter and Oelschlaeger 1997; Donahue and Johnston 1998).

The view of groundwater as a natural resource that must be managed and used wisely is a recent one which is evolving as a result of the overexploitation of the resource. However, confusion and conflicts over what constitutes reasonable use and what is "overexploitation" are made worse by the lack of clearly defined criteria for making effective judgments (Postel 1986; Winter 1995). The wise management of water resources should be approached from two viewpoints: the impact of groundwater manipulation on the natural environment (including groundwater, surface water, and riparian ecosystems) and the volume available for sustainable use.

There is substantial research on the applications of land use regulation to control and influence groundwater quality, contamination, and cleanup, but not much on land use methods and how they affect recharge. Several factors, both physical and social, influence recharge amounts. These include climatic factors, the geology and hydrogeology of an area, land use, growth patterns, and legislation.

Climatic Factors

Climatic factors influence the quantity of groundwater yearly as well as at different times of the year. These factors include precipitation form and type; the quantity or amount of precipitation (storms with longer durations will have a greater total amount of precipitation while shorter duration storms will have greater intensities); the time distribution of the precipitation event (delayed patterns tend to result in greater runoff rates); vegetation cover (heavy vegetation in the spring vs light vegetation in the winter); evapotranspiration rate (higher rates in the summer and lower rates in the winter); and soil moisture (determining the amount of infiltration) (Gleick 1989; Ward and Elliot 1995; Kaczmarek et. al. 1996).

There is a strong linkage between climatic inputs, specifically precipitation, and regional hydrology through the conversion of rainfall to runoff to aquifer recharge. The historical climatic record shows wide variability in precipitation and the occurrence of multiyear droughts. The location of the San Antonio region results in large variations in monthly and annual precipitation amounts (North et. al. 1995; Jensen 1996). The average annual precipitation in San Antonio is approximately 30 inches (762 mm). However, annual precipitation has ranged historically from approximately 13 to 52 inches (330 mm to 1,320 mm) over the past 65 years (Edwards Aquifer Authority 2000). Data indicates that approximately 85 percent of rainfall is recycled through evapotranspiration, and nine percent runs off. The remaining six percent recharges the aquifer (Slade 1984; Sharp and Banner 2000).

Geology and Hydrogeology

The Edwards Aquifer's porous, honeycombed limestone formation is divided into three parts: the Drainage Area, the Recharge Zone and the Artesian Zone (Figure 2 and Figure 3). The Drainage Area, which is about 4,400 mi^2 (11,400 km^2), occurs on the portion of the Edwards Plateau known as the Texas Hill Country. Rainfall on the San Antonio section of the aquifer that averages about 28 inches (711 mm) per year runs off into streams or permeates into the water table aquifer of the plateau. Water table springs

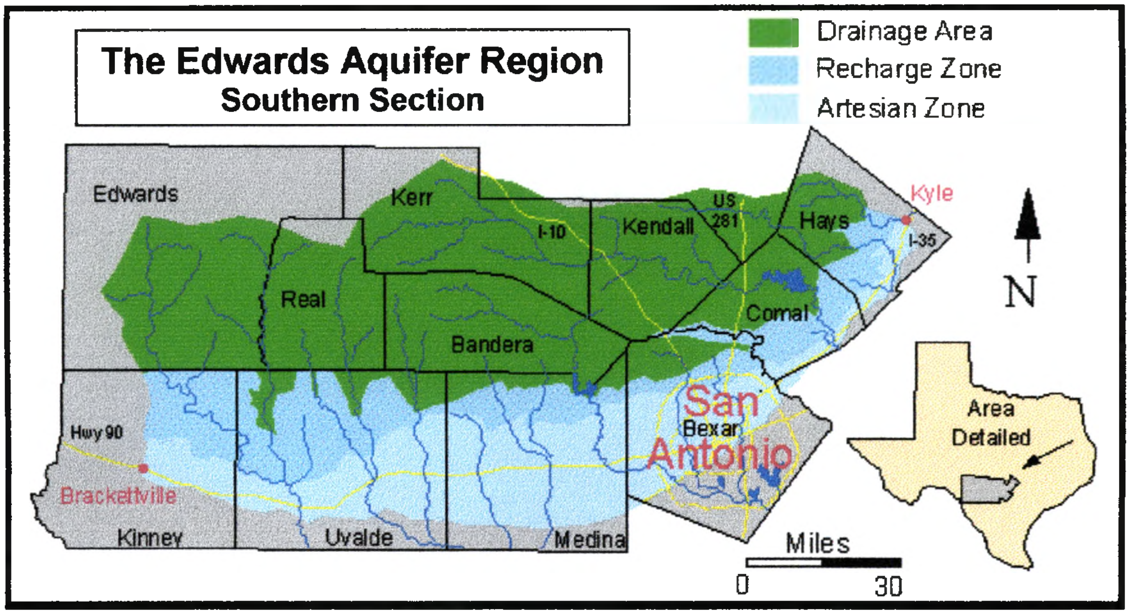

Fig. 2. Southern (San Antonio) Section of the Edwards Aquifer.
Source: Eckhardt n.d.c.

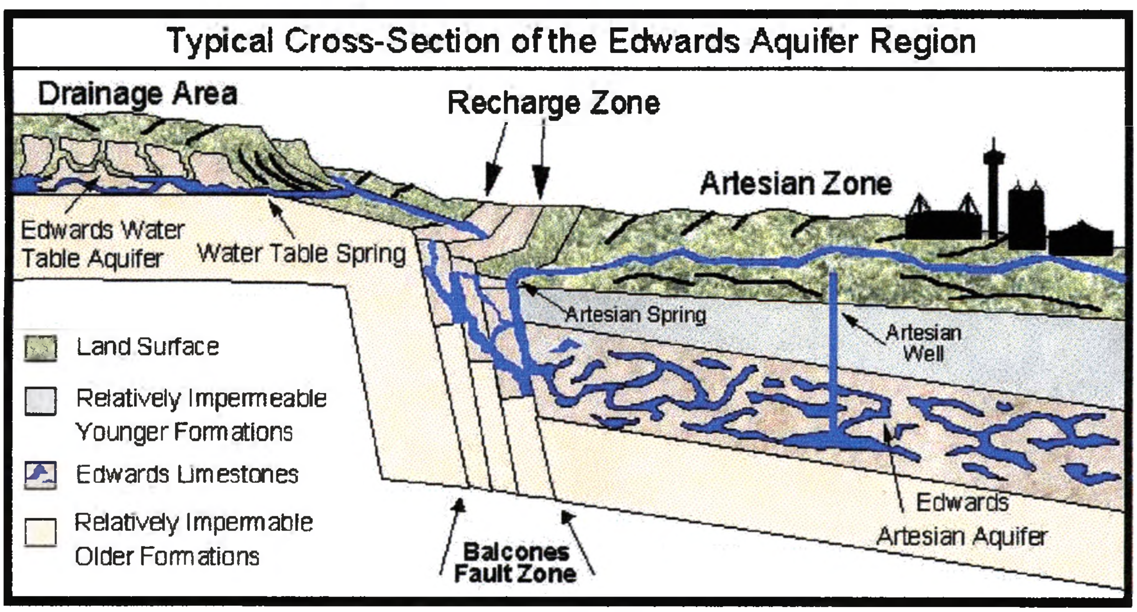

Fig. 3. Cross Section of the Edwards Aquifer.
Source: Eckhardt n.d.b.

then feed streams that flow over relatively impermeable formations until they reach the Recharge Zone (McClay 1989, McClay 1995, Stein and Ozuna 1998; Eckhardt n.d.a).

The Recharge Zone is a 1,500 mi^2 (3,890 km^2) area where highly faulted and fractured Edwards limestone crops out at the land surface allowing water to flow into the aquifer. Recharge occurs when streams and rivers cross the permeable formation and seep underground or when precipitation percolates directly into the Edwards as in-situ recharge. Of the total recharge approximately 80-83 percent is from stream infiltration and the remainder (17-20 percent) comes from direct in-situ recharge (Puente 1978; Slade 1984; Sharp and Banner 2000).

Characterized by sinkholes, sinking streams, caves, springs, and an integrated subsurface drainage system, the aquifer contains extremely high cavernous porosity and permeability characteristic of many karst aquifers. In contrast, aquifers that occur in sand and gravel or in bedrock such as sandstone have a much lower permeability. The high porosity and permeability of the Edwards allow extremely productive water wells, the rapid infiltration of surface water, and the quick response of groundwater levels to rainfall recharge events. While the Edwards Aquifer transmits very large volumes of water, the cavernous porosity provides rapid recharge and limited filtration of surface water (Hammond 1985, Maclay 1989, Maclay 1995, Sharp and Banner 1997).

Flowing artesian wells and springs exist where hydraulic pressure is sufficient to force water up through wells and faults to the surface. Major natural discharges occur at San Marcos Springs and Comal Springs to the northeast of San Antonio. Water moves generally from southwest to northeast through the aquifer, and there are a number of barrier faults that make it impossible for waters in various units of the aquifer to mix together. These faults, along with varying porous and permeable capacities of the limestone, control movement of water in the aquifer (McClay 1989, McClay 1995, Stein and Ozuna 1998; Eckhardt n.d.a).

Aquifer water levels, recharge, and springflow are closely related to precipitation and decrease during periods of low precipitation (Jennings et. al. 1992, Rose 1994, Jensen 1996, Edwards Aquifer Authority 2000). Study of the estimated annual groundwater recharge data since 1934 shows that annual recharge to the San Antonio section of the aquifer has ranged from a low of 43,700 acre-feet (53,900,000 m^3) in 1956 to a high of 2,490,000 (3,066,000,000 m^3) in 1992. For the period of record, spanning from 1934 to 2000, the San Antonio section of the Edwards Aquifer has an average annual recharge of 680,000 acre-feet (839,000,000 m^3) (Edwards Aquifer Authority 2000).

Growth Patterns

The City of San Antonio sprawls a little farther north every day. The north side now has the main post office, international airport, largest churches, highest retail sales and largest shopping malls, medical center, University of Texas campus, largest private employer, bulk of new residential and commercial development, major vacation theme parks and horse track, and the fastest growing population. Nearly every aspect of life has been affected by the northward growth pulling the center of commerce and population to several miles north of downtown (Hicks 1995; Williams 1995a; Edwards 1997).

It has been said that San Antonio growth to the north has been more happenstance than plot. Before fears of southside flooding, development in the hillier north was considered problematic. A series of factors overcame the physical obstacles that once made the rocky elevations of the north side intimidating.

In 1905, Alamo Heights, the first residential area outside the then city limits was developed. The area was growing relatively evenly at this time but Alamo Heights would stretch the parameters. People moved out as highways improved and widened. Roads such as Loop 410 and I-10 were expanded, as a result of federal highway dollars since the Eisenhower administration, opening up outlying areas for development, expansion, and new migration. Outward movement continued with the residential areas of Olmos Park and Terrell Hills in the 1920s, Castle Hills and Hollywood Park in the '50s and '60s, Shavano Park in the 1960s, and Stone Oak, the Crown Ridge, and the Dominion in the 1980s (Hicks 1995; Edwards 1997).

The historic role of the military indirectly shaped growth northward. Kelly Field was built southwest of town in 1916 and Brooks Air Force Base, on the south side, followed in 1918. Randolph Air Force Base opened in the northeast side in 1930. Consequently, San Antonio's military bases, including Fort Sam Houston, had a dramatic effect on the city's population during World War II, as thousands of servicemen arrived. The war also produced a surplus of civilian jobs, which boosted the regional census (Hicks 1995).

Several major developments helped pull San Antonio to the north, including the airport built during the 1940's, the South Texas Medical Center beginning in the late 1950's, United States Automobile Association's (USAA) move to the northwest in 1967 and the 1970 decision to locate the University of Texas at San Antonio at Loop 1604 and

I-10. USAA alone brought a tremendous housing boom, with more than 10,000 employees, making it the city's largest private employer (Williams 1995a).

All these job-generators made the area irresistible for development, but the shift of population may not have moved so far north without the help of political leaders who put in water and sewer lines and streets. Much of the political will to push north came from the Good Government League (GGL), a group that controlled city politics from the mid-1950s until the mid-1970s. The GGL pushed through millions of dollars worth of capital improvement bonds for projects mostly on the north (Hicks 1995; Williams 1995a).

With established neighborhoods on the west and southsides reaching maturity, homebuilders scouted alternative, more affordable sites, especially north of downtown. In 1940, roughly 253,854 people lived within the 36 square miles (93 km^2) of San Antonio, resulting in a population density of 7,051 people per square mile (2,730 people per km^2). In 1999, more than 1 million people were spread across a little more than 400 square miles (1,036 km^2) which approximates 3,000 residents per square mile (1,150 people per km^2). Future restrictions on development over the recharge zone of the Edwards Aquifer on the north side could create incentives for building elsewhere in the city, where land is cheaper and less regulated. The restrictions also could result in the north side as the area to build expensive houses with big yards and not much commercial development nearby (Hicks 1995; Williams 1995a; Bush 1999).

Land Use

Land use plays an important role in groundwater quantity. Vegetation and land use have a marked effect on infiltration. The type of vegetation, season of the year, and land management practices that temporarily modify the near-surface soil conditions will greatly influence infiltration processes. Surface runoff occurs as soon as the infiltration rate is less than the water application rate and surface depressions have been filled (Winter 1995; Marsh 1997; Robins 1998).

In a study conducted by Marsh and Marsh (1994), detailed field data in the Barton Creek watershed revealed that the stairstep topography of the Texas Hill Country has a dramatic impact on the distribution of soils. Based on a general correlation between soil thickness and infiltration capacity, it was shown that the upper risers containing mixed shrub, tree, and grass covers had high infiltration capacities (approximately 4 in/hr or 102 mm/hr) while treads with thin stony soils had low infiltration capacities (less than 1 in/hr or 25 mm/hr). Although this relationship is thoroughly explained in the paper, the method and calculations used to measure infiltration are not discussed, and no actual estimates of recharge are presented.

Currently, the U.S. Geological Survey Water-Resources Investigations 78-10 titled "Method of Estimating Natural Recharge to the Edwards Aquifer in the San Antonio Area, Texas" gives the official method of measuring the recharge of the Edwards Aquifer. Prepared by Celeso Puente in 1978, the basic approach is a water-balance equation in which recharge within a stream basin is the difference between measured streamflow above and below the infiltration area of the aquifer plus the estimated runoff in the zone that includes the infiltration area. This method does not include in-situ recharge as studied by Marsh and Marsh (1994) nor does it account for land use in the calculation of runoff.

Surfaces such as paved roads, sidewalks, parking lots, and buildings allow negligible infiltration. Increases in population in northern Bexar County have brought about increases in development. Eighty-three percent of the new residences between April 1990 and January 1995, including single-family houses, apartments and mobile homes, were located in the northern sector (Hicks 1995, Needham 1995, Williams 1995a, Williams 1995b). About 25 percent of the city's construction between 1990 and 1995 occurred over the Edwards Aquifer recharge zone. About 7,500 of the estimated 46,000 recharge acres suitable for development in this area fall under the old rules for development, meaning that they can be developed with up to 100 percent impervious cover.

Fifty years ago, the problem wasn't so critical. Growth in the Edwards Aquifer recharge zone has caused both quantity and quality problems during wet and dry periods. Population growth and the resulting increase in impervious cover cause runoff to increase making floods larger and more frequent. Seepage from landfills, animal waste, chemical fertilizers and petroleum can endanger the quality of groundwater (Needham 1995, Williams 1996, Edwards 1997, Holly 2000).

Legislation

Finally, legislation plays an important role in groundwater quantity by dictating how and where development may occur. In response to a federal court order pursuant to the 1974 Safe Drinking Water Act, the Texas Natural Resource Conservation Commission (TNRCC) developed rules restricting development and governing activities over the Edwards Aquifer recharge zone to protect the water quality of the aquifer. Some local officials and environmentalists criticized the rules as inadequate to control pollution from rapid urban development (Needham 1998). After the City of San Antonio in a second referendum rejected the Applewhite Reservoir in August 1994, concern about development over the Edwards Aquifer recharge zone blossomed. San Antonio mayor Nelson Wolff assembled the Mayor's Task Force on Water Quality, which included both developers and environmentalists and created San Antonio's first comprehensive regulation for limiting development over its portion of the recharge zone along the northern areas of the city (Bower 1994; Tackett 1994).

The city council passed the plan in January 1995. As a result, rules were implemented which prohibited the sealing of aquifer recharge features such as caves and sinkholes, limited the percentage of impervious cover for future subdivisions, and required developers to observe Best Management Practices (BMPs) in the design and construction of their projects including the use of green spaces, sedimentation ponds, runoff detention structures, and advanced pest management programs within the city limits and extraterritorial jurisdiction of San Antonio. The plan also prohibited industrial and manufacturing plants from storing large quantities of chemicals or dangerous materials on site. Additional gasoline stations were not allowed since new underground storage tanks were prohibited (Bower 1994; Bower and Gonzalez 1995).

After the City of San Antonio passed tougher regulations for the recharge zone within its boundaries, the pressure was on the TNRCC to do the same. Revised in 1999, the purpose of the Edwards Aquifer Rules, found in Title 30 Texas Administrative Code Chapter 213 (30 TAC 213), is to regulate activities having the potential for polluting the Edwards Aquifer and hydrologically connected surface streams in order to protect existing and potential uses of groundwater and maintain Texas Surface Water Quality

Standards. The activities addressed in these regulations are those that pose a threat to water quality; to ensure that the existing quality of groundwater is not degraded; to encourage the propagation and protection of terrestrial and aquatic life; to protect the environment; to manage the operation of existing industries; and to maintain and enhance long term economic health of the state. These rules specifically apply to the Edwards Aquifer. Application to any other aquifers in the state of Texas is not intended (TNRCC 1999b). The new rules extend protection to the contributing zone, which includes all watersheds that feed runoff into rivers and streams that flow over the recharge zone; the recharge zone defined as the area where geologic layers of the aquifer come to the surface and water filters into the aquifer through cracks, fissures, caves, and other openings in these layers; and the transition zone which is characterized by large faults close to the area where most public water supply wells are located (TNRCC 1999b).

In short, the Edwards Aquifer rules regulate construction activities that might contaminate the aquifer or the streams that feed it. Depending on the potential impacts of an activity on water quality in the Edwards Aquifer, these rules may prohibit that activity, allow the activity but regulate it, or exempt the activity from certain regulations. Activities prohibited under the Edwards Aquifer rules include waste disposal wells, new concentrated animal feeding operations (feedlots), land disposal of toxic or hazardous wastes, sewage holding tanks, and new type I Municipal Solid Waste (MSW) landfills. Regulated activities include the construction of buildings, utility stations, utility lines, roads, highways, or railroads; clearing, excavation, or any other activity that alters or disturbs the topographic, geologic, or existing recharge characteristic of a site; and the installation of underground or above ground storage tanks on either the recharge zone or the transition zone (TNRCC, 1999a).

Additional legislative challenges faced the area through Texas Senate Bill 1, passed by the 75th Legislature in 1997, which required the establishment of water planning regions in Texas and the development of a statewide water plan (Texas Water Development Board 1997). The bill required that new water supply projects be selected and approved through a regional planning process and ultimately be incorporated into the statewide water plan. Because the constant rise in population has already stressed their finite water supply, both San Antonio and the surrounding areas have actively promoted conservation and sought alternative sources of water to foster growth.

The goal of the San Antonio Water System (SAWS) water plan is to "...ensure, to the significant extent that water has a role, in the pursuit of an economically and environmentally sustainable community in the future" (San Antonio Water System 1998). Good regional solutions require strong coalitions between regional interests. "The solutions will need to be balanced and sustainable over time to ensure the long term economic prosperity and environmental health that is currently enjoyed in south-central Texas" (San Antonio Water System 1998).

Several fundamental principles that guided the development of the plan seem to encompass pseudosolutions. For example, it is stated "...water will be provided in sufficient quantities to ensure that growth is not limited by water" (San Antonio Water System 1998). These principles also propose that "...a margin of excess supply over demand should be on hand to provide for economic development and for excess supply during critical periods. Water supply should be available to meet two to five years of projected growth in the short-term and meet a minimum of ten years projected growth in the long-term" (San Antonio Water System 1998).

It will no longer be sufficient to define management objectives to satisfy only the operators and direct users of groundwater. In some cases, a complete reordering of priorities may be required. Consideration must be given to broader objectives that recognize groundwater as a resource that serves many diverse functions, including an ecological one. Increased pumping, habitat destruction, and decreased water quality have reduced springflows which are home to endangered species. Instead of focusing primarily on continued economic growth, research needs to be focused on the linkages between population density, consumption, distribution patterns and aquifer recharge.

CHAPTER 3

METHOLODOGY

The purpose of this study is to examine development over the Edwards Aquifer recharge zone in the San Antonio/Bexar County area during the period 1970-2000. The study area comprises a 127 mi^2 (328 km^2) area. The recharge zone continues across much of the northern segment of Loop 1604, and at the county line extends westward along Cibolo Creek and part of Balcones Creek (Figure 4).

Calculation of Impervious Cover as a Function of Land Use and Population Density

Recharge of the Edwards Aquifer occurs when streams and rivers cross the permeable formation and seep underground or when precipitation permeates directly into the aquifer. Therefore, the measurement of impervious cover refers to the inability of water to penetrate those areas of the land surface occupied by manmade structures.

Stephen J. Stankowski studied changes in land use and their effect on the amount of impervious cover in USGS Professional Paper 800-B (1972). Based on correlations between population density and the proportions of land area for New Jersey, a set of equations was developed to convert population density to amounts of impervious cover. To perform this calculation for the recharge zone in San Antonio/Bexar County, data was obtained through a review of U.S. Census Bureau reports for 1970, 1980, 1990, and 2000,

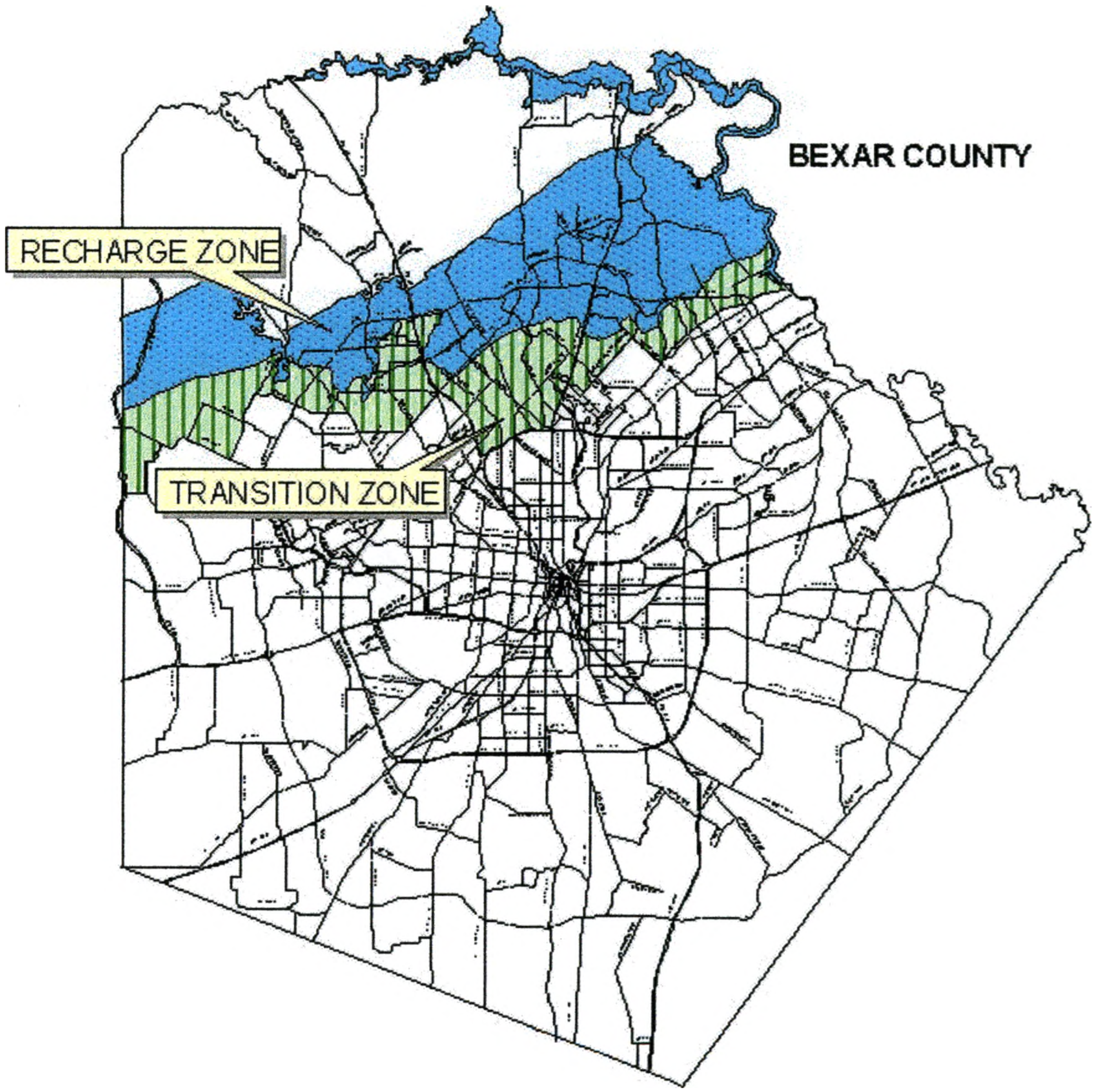

Fig. 4. Edwards Aquifer Recharge and Transition Zone in Bexar County.
Source: San Antonio Water System Source Water Watershed Protection

in each of six urban and suburban land use categories. The proportions of land use have been, in turn, weighted by the average percentage of impervious area found in each land use category.

In order to transform the details of land use patterns to a single numerical index that characterizes the hydrology of an urban area, a range of average percentages of impervious cover representing the effects of typical modifications found in each land use category have been used and are identified in Table 1.

Table 1
Impervious Land Area Within Land Use Categories

Land use Category	Impervious Cover (percent)		
	Low	Intermediate	High
Single Family Residential	12	25	40
Multiple Family Residential	60	70	80
Commercial	80	90	100
Industrial	40	70	90
Public and Quasi-Public	50	60	75
Conservational, recreational, and open	0	0	0

Source: Stankowski 1972

Using each set of estimates for percentages of impervious cover as weighting factors, the impervious cover in each census tract of the study area has been determined as the sum of the weighted proportions of land area in each land use category using the following equations developed by Stankowski (1972):

$$I_{low}=0.017D^{1.165-0.094\log D}$$

$$I_{intermediate}=0.0218D^{1.206-0.100\log D}$$

$$I_{high}=0.0263D^{1.247-0.108\log D}$$

where

I_{low}, $I_{intermediate}$, I_{high}= percentages of impervious land area based on the low, intermediate, and high impervious area weighting factors and

D= population density in persons per square mile.

Calculation of Runoff Estimates

The comparison of runoff between 1970 and 2000 has been computed by utilizing the USGS SCS TR-55 model which calculates runoff as a function of land use and land cover, soil characteristics, and antecedent moisture assuming that the amount of runoff produced from a storm increases as the storm continues. In this model, infiltration losses are combined with surface storage to give an estimate of net surface runoff expressed by the equation (Soil Conservation Service 1972):

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)}$$

where

Q= the accumulated runoff or rainfall excess in inches

P= the rainfall depth in inches

I_a= the initial abstractions in inches and includes surface storage, interception, and infiltration prior to runoff commonly approximated as 0.2S (Soil Conservation Service 1972)

S= a parameter given by

$$S = \frac{1000}{CN} - 10$$

where CN is known as the curve number (Soil Conservation Service 1972).

To account for the infiltration characteristics of soils, the U.S. Natural Resource Conservation Service (previously known as the U.S. Soil Conservation Service) has divided soils into four hydrologic soil groups, defined in Table 2. These soil groups were used to identify typical curve numbers for antecedent soil moisture conditions dependent on land use, shown in Table 3, which in turn calculate the amount of direct runoff in comparison to rainfall.

Soil characteristics were taken from the Bexar County Soil Survey while precipitation data was acquired from the Climatological Data for Texas which supplies monthly and yearly precipitation data as well as long term averages.

Calculation of Stream Recharge and In-situ Recharge

Total recharge of the Edwards Aquifer can be expressed as

Total recharge = Stream Recharge + In-situ Recharge.

Stream recharge has been calculated based upon runoff produced under 1970 to 2000 land use conditions from the SCS TR-55 model and current stream recharge modeling methods developed by the USGS and the Edwards Aquifer Authority. Changes in stream discharge affect stream width, depth and velocity, which in turn affect the amount of stream infiltration recharge. At a given stream cross section, the wetted perimeter is expressed as the width plus twice the depth. The greater the wetted perimeter, the greater the surface area for aquifer recharge. Leopold and Maddock (1953) explored the relationship between discharge and changes in channel depth, width, and velocity in the USGS Professional Paper 252. The relationship of discharge to width, depth, and velocity at a given river cross section can be expressed as:

Table 2
Hydrologic Soil Groups

Group A	(Low runoff potential) Soils having high infiltration rates even when thoroughly wetted. These consist chiefly of deep, well-drained sands and gravels. These soils have a high rate of water transmission **(final infiltration rate greater than 0.3 inches/hr).**
Group B	Soils having moderate infiltration rates when thoroughly wetted. These consist of chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission **(final infiltration rate 0.15 to 0.30 inches/hr).**
Group C	Soils having slow infiltration rates when thoroughly wetted. These consist of soils with a layer that impedes downward movement of water or soils with moderately fine to fine texture. These soils have a slow rate of water transmission **(final infiltration rate 0.05 to 0.15 inches/hr).**
Group D	(High runoff potential) Soils having very slow infiltration rates when thoroughly wetted. These consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission **(final infiltration rate less than 0.05 inches/hr).**

Source: Soil Conservation Service 1984

Table 3
Curve Numbers for Antecedent Soil Moisture Condition II

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Commercial, row houses and townhouses	80	85	90	95
Fallow, poor condition	77	86	91	94
Cultivated with conventional tillage	72	81	88	91
Cultivated with conservation tillage	62	71	78	81
Lawns, poor condition	58	74	82	86
Lawns, good condition	39	61	74	80
Pasture or range, poor condition	68	79	86	89
Pasture or range, good condition	39	61	74	80
Meadow	30	58	71	78
Pavement and roofs	100	100	100	100
Woods or forest thin stand, poor cover	45	66	77	83
Woods or forest, good cover	25	55	70	77
Farmsteads	59	74	82	86
Residential ¼ acre lot, poor condition	73	83	88	91
Residential ¼ acre lot, good condition	61	75	83	87
Residential ½ acre lot, poor condition	67	80	86	89
Residential ½ acre lot, good condition	53	70	80	85
Residential 2 acre lot, poor condition	63	77	84	87
Residential 2 acre lot, good condition	47	66	77	81
Roads	74	84	90	92

Source: Soil Conservation Service 1984

$$w=aQ^{b} \qquad d=cQ^{f} \qquad u=kQ^{m}$$

$$P=2d+w$$

where

w= width

d= depth

u= velocity

Q= discharge

P=wetted perimeter

a,c,k= numerical coefficients given by

$$a*c*k=1$$

where a=34, b=0.095, c=0.32[1]

b, f, m= exponents given by

$$b+f+m=1$$

where b= 0.26, f= 0.40, m= 0.34 (Leopold and Maddock 1953)

Increases in total channel recharge were calculated by yearly U.S. Geological Survey estimates of channel recharge by the ratio of new wetted perimeter to old wetted perimeter.

In-situ recharge can be expressed as the difference between groundwater recharge and springflow, groundwater pumping, and stream infiltration. Therefore,

In-situ Recharge + Stream Recharge = Springflow + Groundwater Pumpage $\pm$ Storage.

Assuming storage is equal to zero over the long term,

In-situ Recharge = Springflow + Groundwater Pumpage - Stream Recharge.

[1] Values calculated from measurements of recharge streams in the Recharge Zone at the Southwest Texas State University Freeman Ranch, 2000-2002.

In-situ recharge of the Edwards Aquifer was estimated as the maximum decrease of in-situ recharge by multiplying the total in-situ recharge (assumed to be 20% of total recharge) by the ratio of the percent impervious cover in the base year of 1970 with that for the year of record. Therefore,

Potential In-situ Recharge for Year of Record = .20(Total Recharge of Year of Record)

$$\text{Actual Year of Record In-situ Recharge} = \frac{\text{1-Year of Record Impervious Cover}}{\text{1-Base Year (1970) Impervious Cover}} * \text{(Potential In-Situ Recharge)}$$

An increase in peak discharge was assumed to produce a greater amount of stream recharge as a result of a larger contributing wetted perimeter.

Analysis and Presentation of Results

To determine whether a relationship exists between increased development and the recharge of the Edwards Aquifer, total annual recharge for the years 1970 to 2000 was compared to the total annual in-situ recharge plus stream channel recharge. This recharge data was accessed through Water Resources Data, Texas for Water Years 1970 to 2001.

A graphic interpretation of findings is presented in a series of maps and tables documenting changes in impervious cover and recharge amounts over the Edwards Aquifer recharge zone in the San Antonio/Bexar County area for the years 1970, 1980, 1990, and 2000. ArcView GIS software and basemap data acquired from the U.S. Census Bureau Tiger Files, Edwards Aquifer Authority, and the Texas Natural Resources Information System (TNRIS) were used.

CHAPTER 4

STUDY RESULTS

An examination of the effects of development on recharge of the Edwards Aquifer in San Antonio/Bexar County involved quantifying the amount of impervious cover, the amount of runoff, and the amount of stream, in-situ, and total recharge.

Quantification of Impervious Cover

The first step in calculating the amount of impervious cover was to identify which census tracts fall in the recharge zone of the Edwards Aquifer in San Antonio/Bexar County. Census tracts usually have between 2,500 and 8,000 persons, with the spatial size of the tracts depending on the density of the settlement. Census tracts are divided due to large population growth, or combined as a result of substantial population decline. Table 4 represents the tract comparability from census years 1970, 1980, 1990, and 2000. This study covers only tracts over the recharge zone identified in Table 5. Population density was calculated for each tract in the study area and is listed in Table 6. The 1980 study year was excluded because census reports yield only partial count data for tracts lying in the study area.

Table 7 represents the increases in population density and the subsequent increases in impervious cover from 1970 to 2000. The values in the three right hand

Table 4
Tract Comparability 1970 to 1980 to 1990 to 2000

1970	1980	1990	2000
1211	1211.01	1210 (pt)	1210 (pt)
			·1211.12 (pt)
		1211.03	1211.09
			1211.1
		1211.04	1211.11
			1211.12 (pt)
		1211.05	1210 (pt)
			1211.12 (pt)
			1211.14
	1211.02	1211.06	1211.17
			1211.18
		1211.07	1211.15
			1211.16
			1917 (pt)
		1211.08	1211.08
			1917 (pt)
1218	1218	1218.01	1218.01
		1218.02	1812.02
		1218.03	1218.03
		1218.04	1218.04
		1218.05	1218.06
			1218.07
	1219 (pt)		
1219	1219 (pt)	1219.01	1219.01 (pt)
		1219.02	1219.01 (pt)
			1219.02
1818	1818 (pt)		
1819	1818 (pt)	1818.01	1818.01
		1818.02	1818.06
			1818.07
			1818.08
		1818.03	1818.03
			1818.10 (pt)
		1818.04	1818.09
			1818.10 (pt)

Table 4
Tract Comparability 1970 to 1980 to 1990 to 2000

1970	1980	1990	2000
		1818.05	1817.04 (pt)
			1818.11
			1818.12
	1819	1819	1819
1820	1820	1820	1820
1821	1821	1821	1821.01
			1821.02
			1821.03
			1821.04
1914	1914	1914.01	1914.05 (pt)
			1914.06
		1914.02	1914.07 1914.02 (pt)
		1914.03	1914.02 (pt)
			1914.03
		1914.04	1914.08
			1914.09
		1914.05	1914.05 (pt)
1915	1915	1915.01	1915.01 (pt)
		1915.02	1915.02
1916	1916	1916	1916 (pt)
1917	1917 (pt)	1917	1914.02
1918	1917 (pt)		1917 (pt)
	1918	1918.01	1916 (pt)
			1918.04
			1918.05
		1918.02	1918.02
		1918.03	1915.01(pt)
			1918.03

Source: Bureau of the Census 1970; Bureau of the Census 1980; Bureau of the Census 1990; Bureau of the Census 2000.

Table 5
Edwards Aquifer Tract Comparability 1970 to 1980 to 1990 to 2000

1970	1980	1990	2000
1211 (pt)	1211.02	1211.06	1211.17
			1211.18
		1211.07	1211.16
1218 (pt)/1219	1219	1219.01	1219.01
		1219.02	1219.02
1818/1819 (pt)	1818	1818.01	1818.01
		1818.02	1818.06
		1818.05	1818.12
1819 (pt)	1819	1819	1819
1820	1820	1820	1820
1821	1821	1821	1821.04
1914	1914	1914.01	1914.06
			1914.07
		1914.05	1914.05
1915	1915	1915.01	1915.01
		1915.02	
1916	1916	1916	1916
1917/1918 (pt)	1917	1917	1917
1918 (pt)	1918	1918.01	1918.05
		1918.02	1918.02
		1918.03	1918.03

Source: Bureau of the Census 1970; Bureau of the Census 1980; Bureau of the Census 1990; Bureau of the Census 2000.

Table 6
Population Density for Census Tracts within the Edwards Aquifer Recharge Zone in Bexar County
1970-2000

1970			
Census Tract	**Persons**	**Area**	**Population Density**
		mi^2	**$people/mi^2$**
1211	934	22.4	42
1218	no data	10.6	---
1219	no data	57.9	---
1818/1819	3104	35.0	89
1820	1715	4.9	350
1821	1362	4.9	278
1914	1058	11.1	95
1915	1311	6.6	199
1916	60	48.9	1
1917	3481	5.5	633
1918	no data	23.3	---

Source: Bureau of the Census 1970.

1980			
Census Tract	**Persons**	**Area**	**Population Density**
		mi^2	**$people/mi^2$**
1211.02	11,090(p)	7.0	1,584
1219	35 (p)	57.9	1
1818	8,144 (p)	21.0	388
1819	608 (p)	14.0	43
1820	610 (p)	14.9	41
1821	no data	14.9	---
1914	3,245 (p)	11.1	293
1915	1,458 (p)	6.6	221
1916	no data	48.9	---
1917	39 (p)	5.5	7
1918	72 (p)	23.3	3

Note: Data indicated with (p) represent partial counts.
Source: Bureau of the Census 1980.

Table 6
Population Density for Census Tracts within the Edwards Aquifer Recharge Zone in Bexar County
1970-2000

1990			
Census Tract	**Persons**	**Area**	**Population Density**
		mi^2	**$people/mi^2$**
1211.06	6,208	3.2	1,940
1211.07	9,185	2.1	4,374
1219.01	1,186	52.0	23
1219.02	3,613	5.9	612
1818.01	2,386	2.7	900
1818.02	6,624	7.9	840
1818.05	6,885	5.5	1,252
1819	2,373	14.0	170
1820	2,411	14.9	162
1821	7,412	14.9	497
1914.01	4,472	4.0	1,118
1914.05	6,515	3.5	1,861
1915.01	4,467	4.2	1,064
1915.02	5,920	2.4	2,498
1916	7	48.9	0.14
1917	6,553	5.5	1,191
1918.01	3,884	2.8	1,382
1918.02	677	5.9	115
1918.03	1,353	14.6	93

Source: Bureau of the Census 1990.

Table 6
Population Density for Census Tracts within the Edwards Aquifer Recharge Zone in Bexar County
1970-2000

2000			
Census Tract	**Persons**	**Area**	**Population Density**
		mi^2	**people/mi^2**
1211.17	3,678	1.1	3,406
1211.18	5,718	2.1	2,723
1211.16	4,704	1.2	4,021
1219.01	2,331	52.0	45
1219.02	8,616	5.9	1,460
1818.01	6,031	2.7	2,276
1818.06	4,677	4.2	1,114
1818.12	11,561	4.1	2,855
1819	4,859	14.0	347
1820	3,868	14.9	260
1821.04	3,180	40.7	78
1914.05	7,732	3.5	2,209
1914.06	6,364	1.8	3,536
1914.07	6,982	2.3	3,076
1915.01	6,447	4.2	1,535
1916	16	48.9	0.33
1917	8,092	5.5	1,471
1918.02	4,197	5.9	711
1918.03	4,418	14.6	303
1918.05	43,149	55.3	781

Source: Bureau of the Census 2000.

Table 7
Percentage of Impervious Area
1970-2000

1970				
Census Tract	**Population Density**	**I_{low}**	**$I_{intermediate}$**	**I_{high}**
	people/mi^2	**% area**	**% area**	**% area**
1211	42	0.74	1.07	1.44
1218	no data	no data	no data	no data
1219	no data	no data	no data	no data
1818/1819	89	1.39	2.03	2.75
1820	350	3.85	5.75	7.82
1821	278	3.28	4.88	6.65
1914	95	1.47	2.16	2.92
1915	199	2.58	3.82	5.19
1916	1	0.02	0.03	0.03
1917	633	5.71	8.55	11.63
1918	no data	no data	no data	no data

Source: Bureau of the Census 1970; Stankowski 1972.

Table 7
Percentage of Impervious Area
1970-2000

1990				
Census Tract	**Population Density**	I_{low}	$I_{intermediate}$	I_{high}
	people/mi^2	**% area**	**% area**	**% area**
1211.06	1,940	11.08	16.69	22.51
1211.07	4,374	16.83	25.34	33.77
1219.01	23	0.44	0.62	0.82
1219.02	612	5.59	8.37	11.39
1818.01	900	7.11	10.68	14.50
1818.02	840	6.81	10.23	13.89
1818.05	1,252	8.65	13.02	17.63
1819	170	2.29	3.39	4.60
1820	162	2.21	3.27	4.44
1821	497	4.88	7.30	9.94
1914.01	1,118	8.10	12.18	16.51
1914.05	1,861	10.83	16.32	22.02
1915.01	1,064	7.86	11.82	16.03
1915.02	2,498	12.69	19.12	25.71
1916	0.14	0.00	0.00	0.00
1917	1,191	8.41	12.65	17.14
1918.01	1,382	9.16	13.79	18.66
1918.02	115	1.70	2.50	3.39
1918.03	93	1.44	2.11	2.85

Source: Bureau of the Census 1990; Stankowski 1972.

Table 7
Percentage of Impervious Area
1970-2000

2000				
Census Tract	**Population Density**	I_{low}	$I_{intermediate}$	I_{high}
	people/mi^2	**% area**	**% area**	**% area**
1211.17	3,406	14.88	22.42	30.00
1211.18	2,723	13.28	20.01	26.86
1211.16	4,021	16.15	24.33	32.47
1219.01	45	0.79	1.14	1.53
1219.02	1,460	9.46	14.24	19.25
1818.01	2,276	12.08	18.20	24.50
1818.06	1,114	8.08	12.15	16.47
1818.12	2,855	13.61	20.50	27.51
1819	347	3.83	5.71	7.78
1820	260	3.13	4.65	6.33
1821.04	78	1.25	1.83	2.47
1914.05	2,209	11.89	17.91	24.12
1914.06	3,536	15.16	22.84	30.55
1914.07	3,076	14.14	21.30	28.54
1915.01	1,535	9.73	14.65	19.80
1916	0	0.00	0.01	0.01
1917	1,471	9.50	14.30	19.34
1918.02	711	6.14	9.22	12.53
1918.03	303	3.48	5.19	7.06
1918.05	780.69	6.51	9.78	13.28

Source: Bureau of the Census 2000; Stankowski 1972.

columns are percentages of impervious area based on the low, intermediate, and high weighing factors as described by Stankowski in USGS Professional Paper 800-B (1972). Visual representation of population data is displayed in Figures 5 through 7, while population density is displayed in Figures 8 through 10 and impervious cover in Figures 11 through 13.

Runoff Estimates

Use of the USGS SCS TR-55 model required the identification of the different soil types and their infiltration characteristics, land use and land cover, and precipitation amounts for the study area.

The recharge zone of the Edwards Aquifer is dominated by three soil associations: the Crawford-Bexar, Tarrant-Brackett and the Lewisville-Houston Black, terrace associations (Figure 14). The soils in the Crawford-Bexar association are moderately deep and have a dark brown to reddish brown color. These stony soils have developed over broken limestone. The Tarrant-Brackett association are clayey, very dark grayish-brown soils that on the surface have various amounts of stones, cobblestones, and gravel with moderate permeability. They are underlain by Glen Rose limestone and Edwards limestone. The Lewisville-Houston Black terrace association are predominantly deep clays and silty clays dark brown to dark grayish brown in color. These moderately permeable soils form in old alluvium (Soil Conservation Service 1962). The characteristics of these soils would place them in the Hydrologic Soil Group B.

The clay rich soils and land use of the study area during the period 1970 to 2000 resulted in high curve numbers. The curve numbers for the study period were 82 in 1970, 83 in 1980, 84 in 1990 and 85 in 2000. Defining the characteristics of the study area as

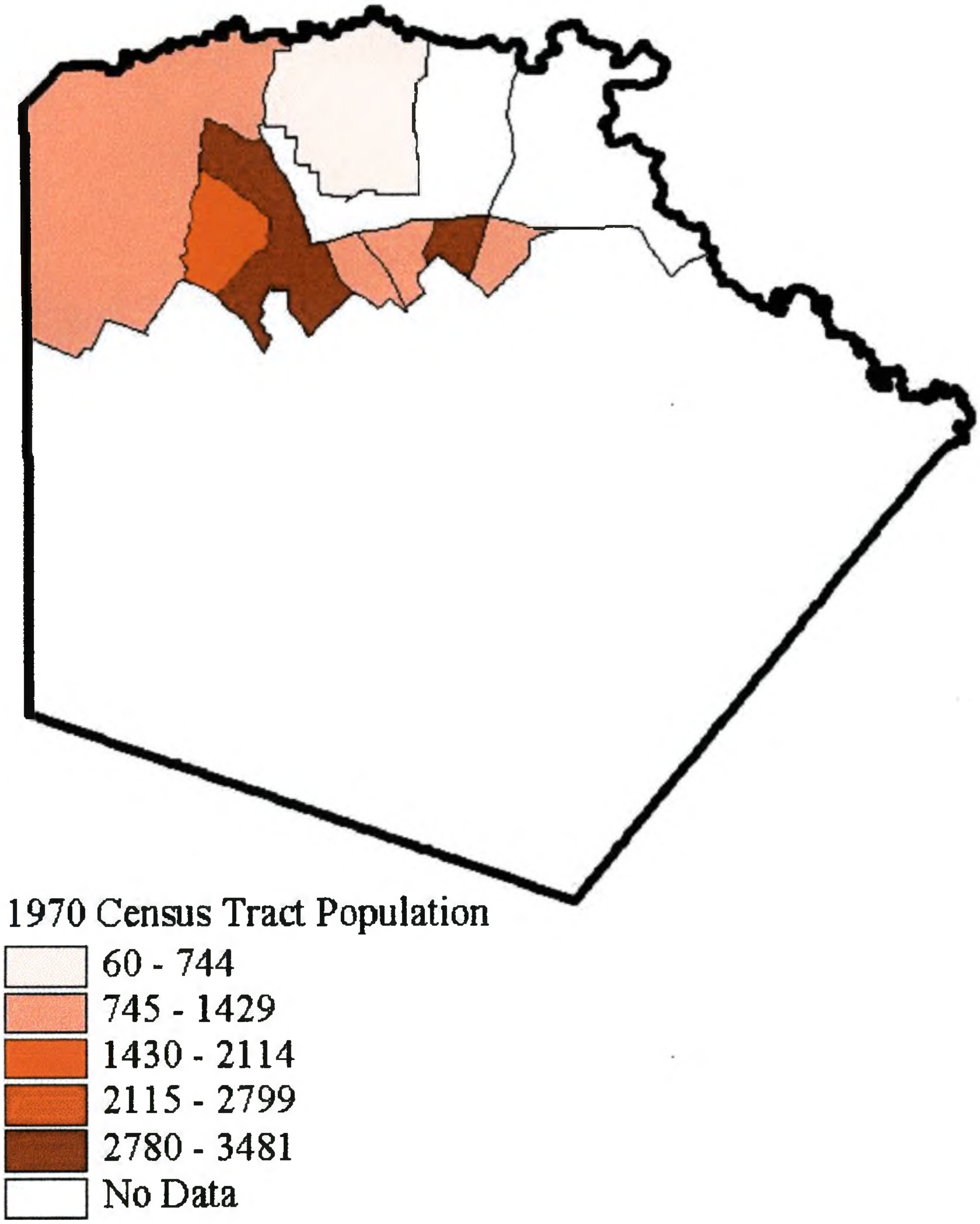

Fig. 5. 1970 Edwards Aquifer Census Tract Population.

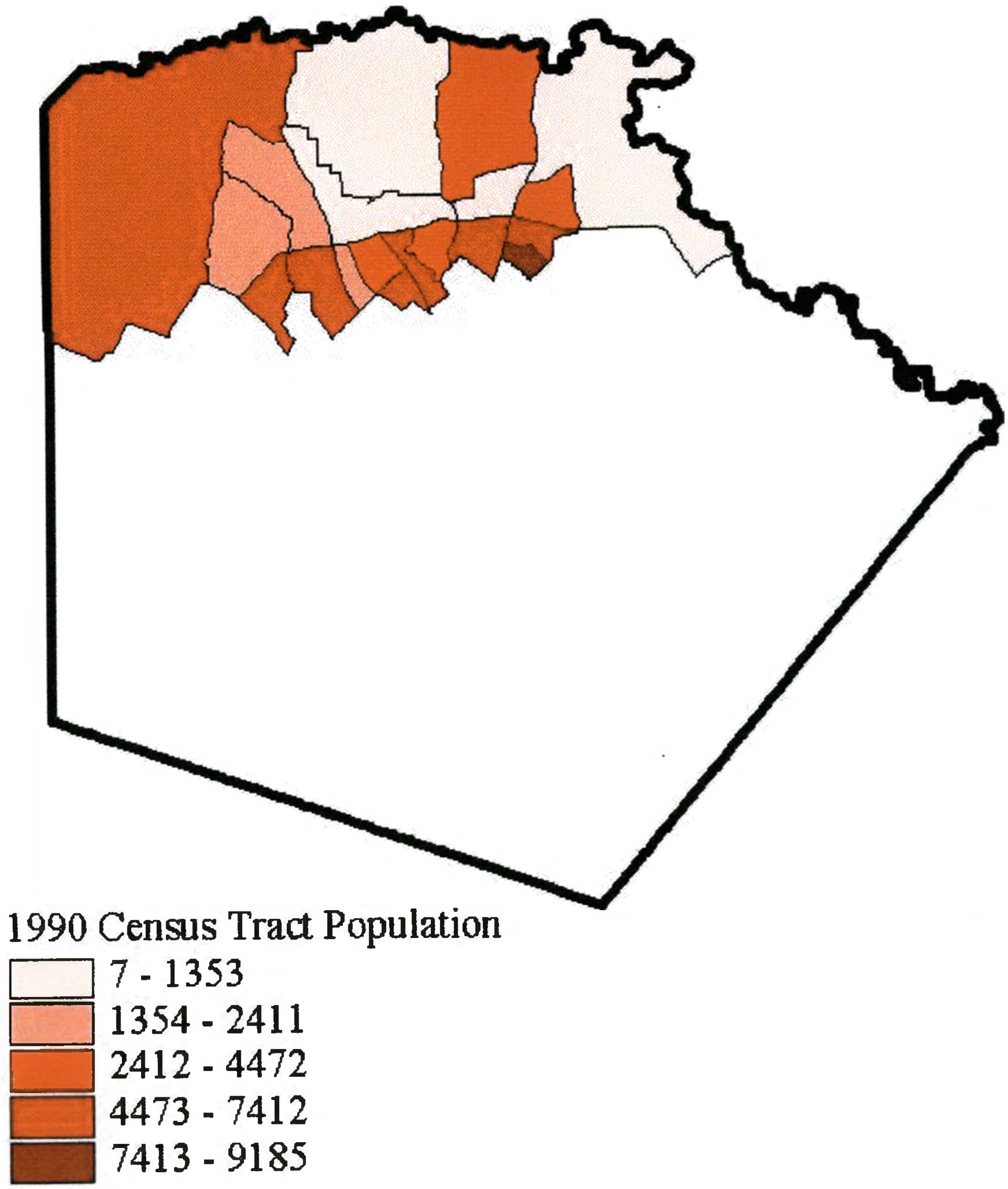

Fig. 6. 1990 Edwards Aquifer Census Tract Population.

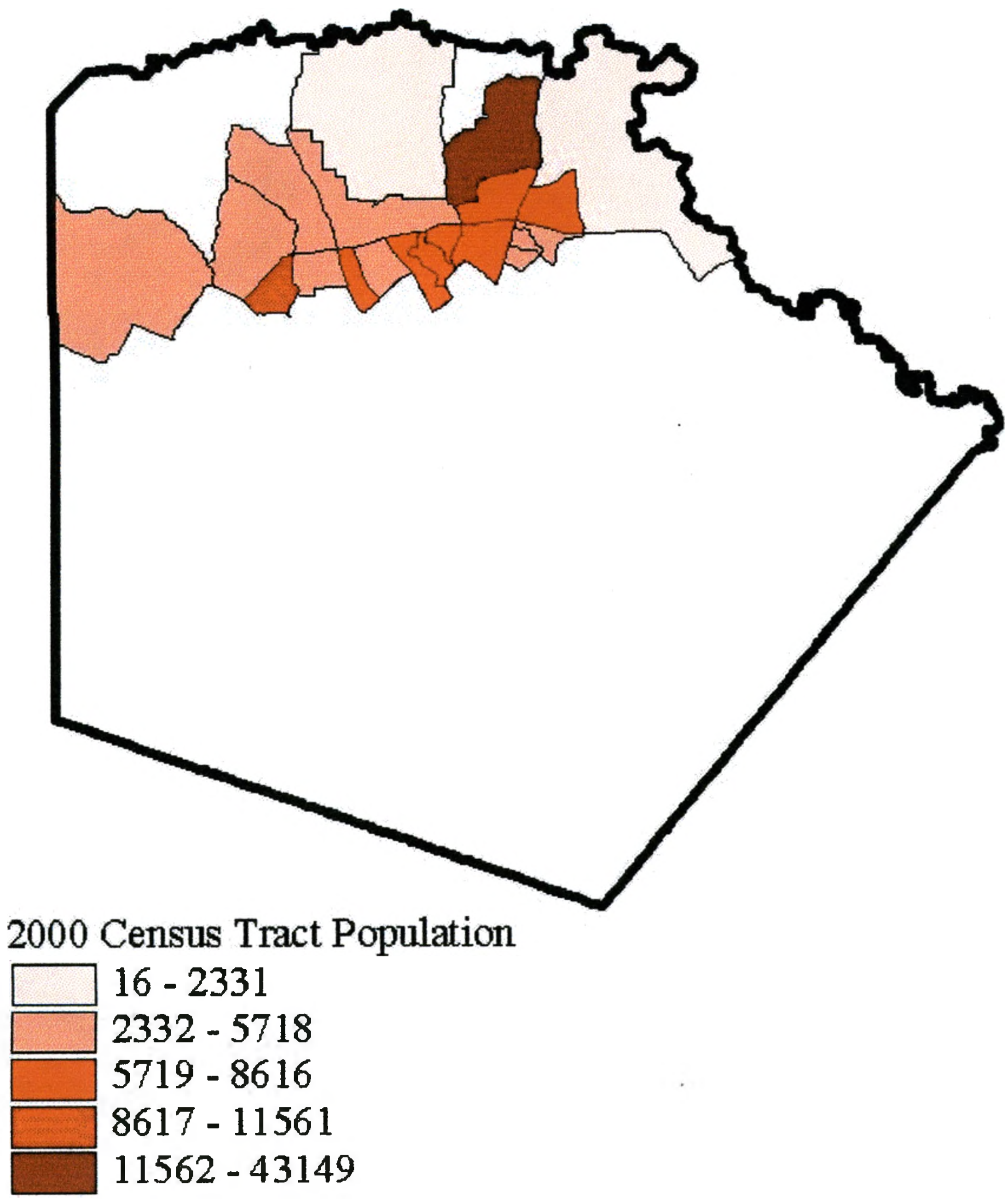

Fig. 7. 2000 Edwards Aquifer Census Tract Population

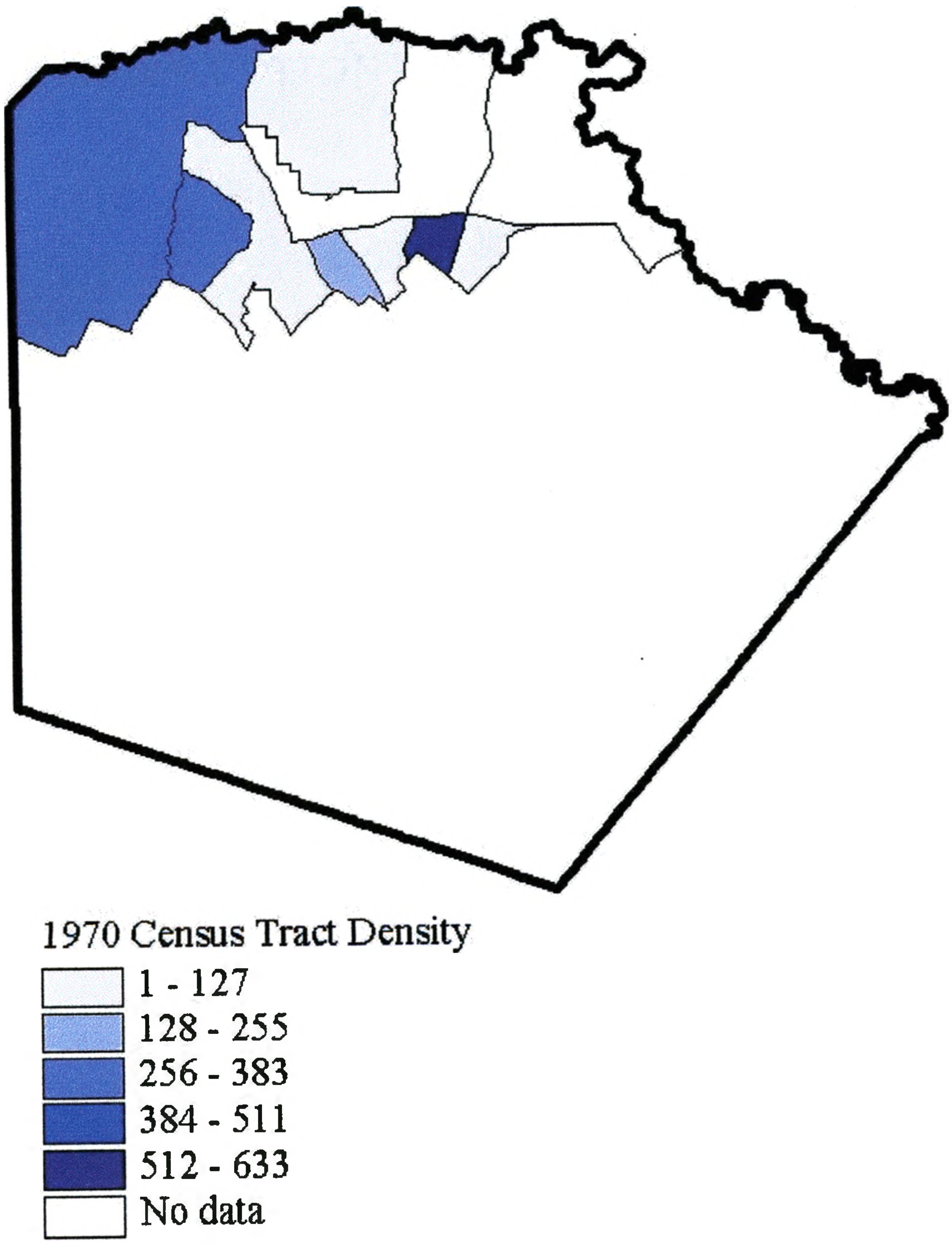

Fig. 8. 1970 Edwards Aquifer Census Tract Population Density
in Persons per Square Miles.

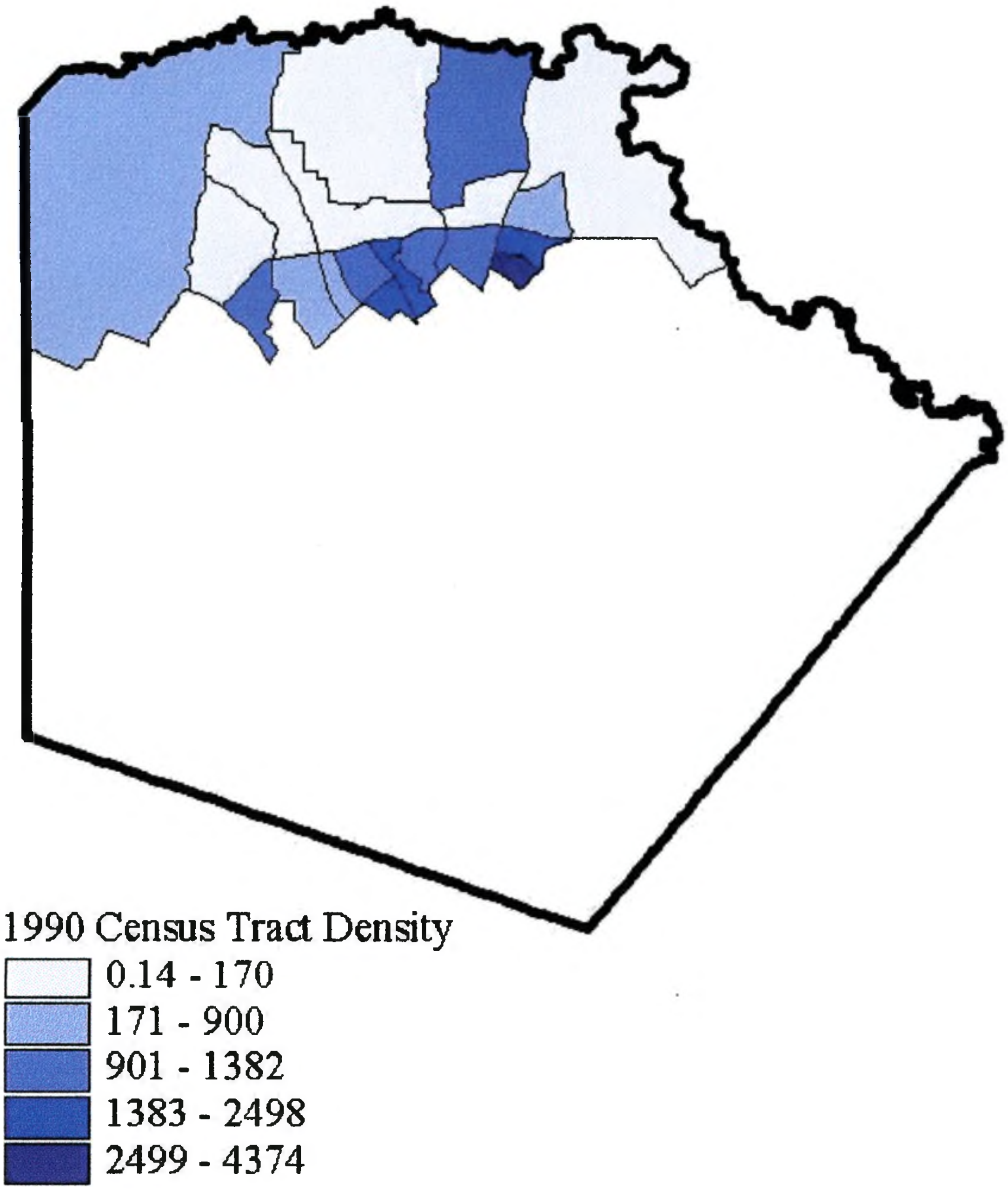

Fig. 9. 1990 Edwards Aquifer Census Tract Population Density
in Persons per Square Miles.

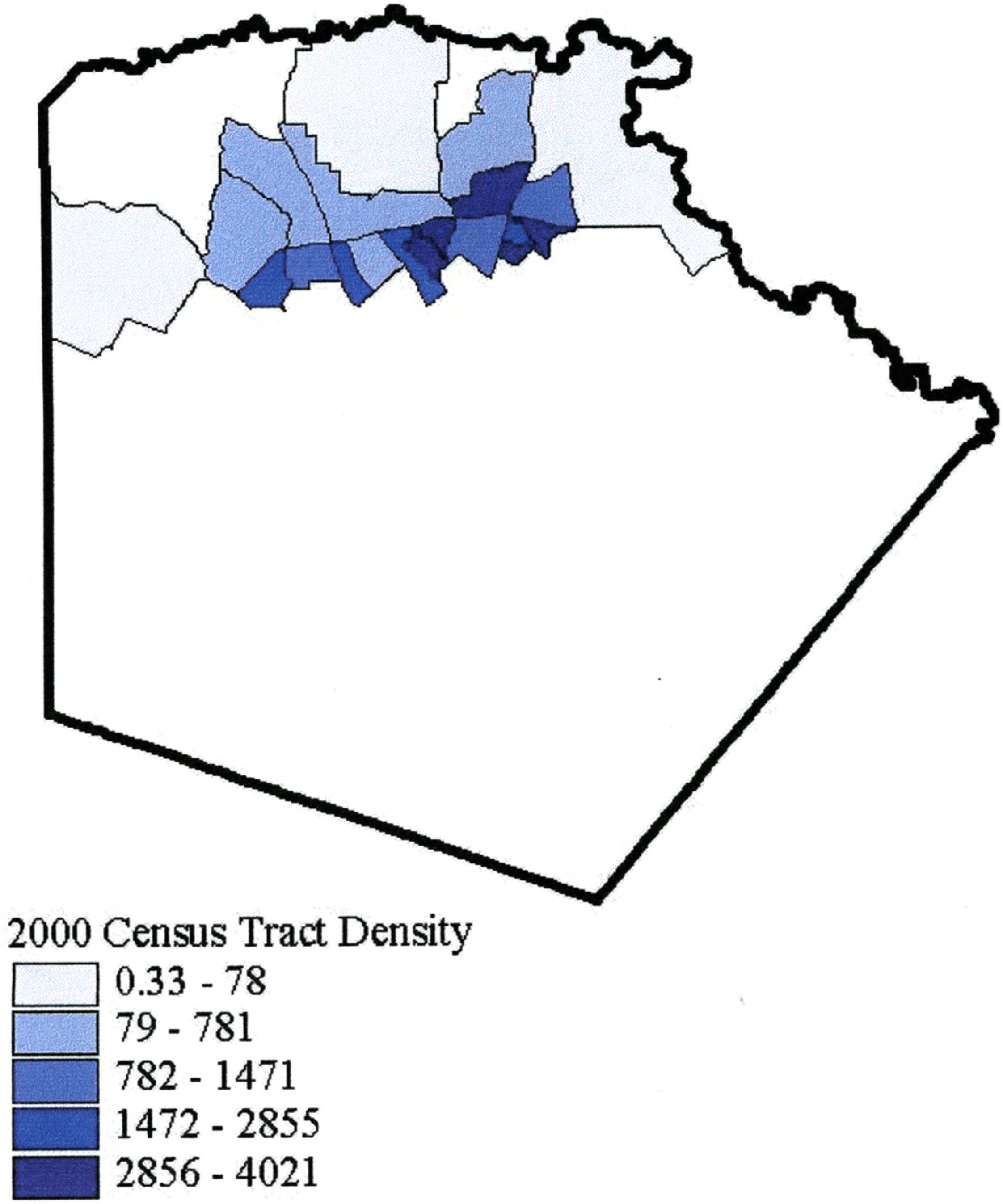

Fig. 10. 2000 Edwards Aquifer Census Tract Population Density
in Persons per Square Miles.

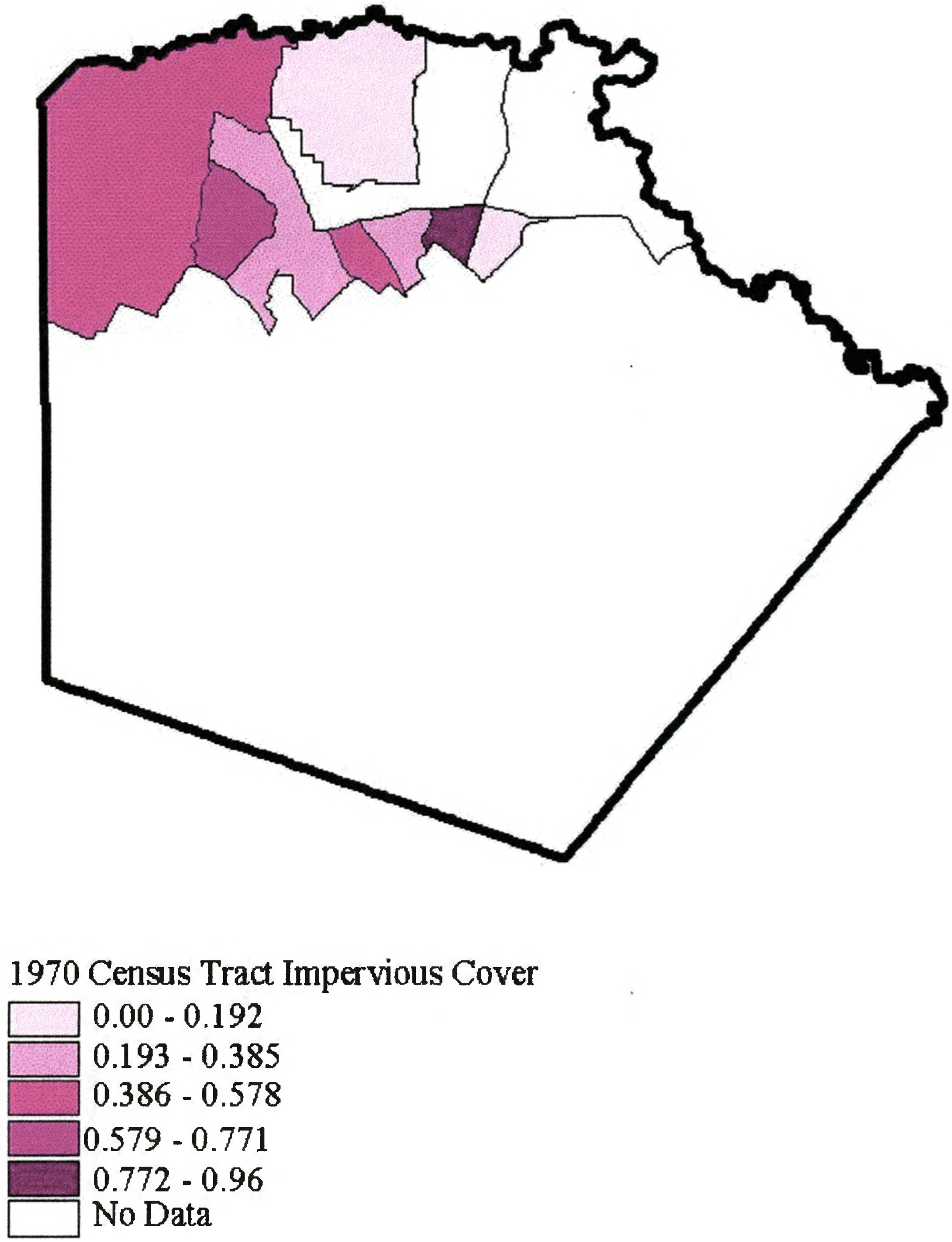

Fig. 11. 1970 Edwards Aquifer Census Tract Impervious Cover in Square Miles.

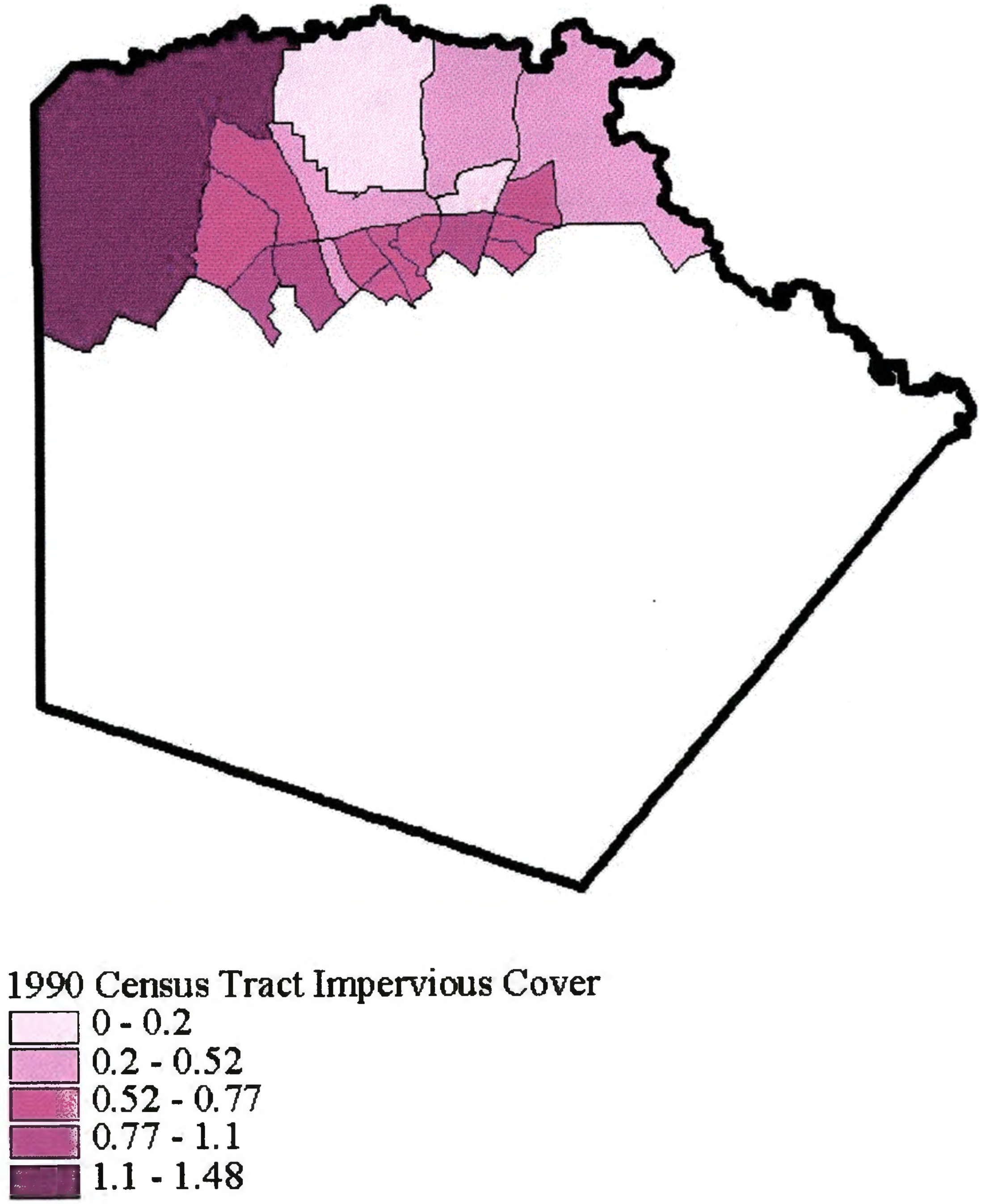

Fig. 12. 1990 Edwards Aquifer Census Tract Impervious Cover in Square Miles.

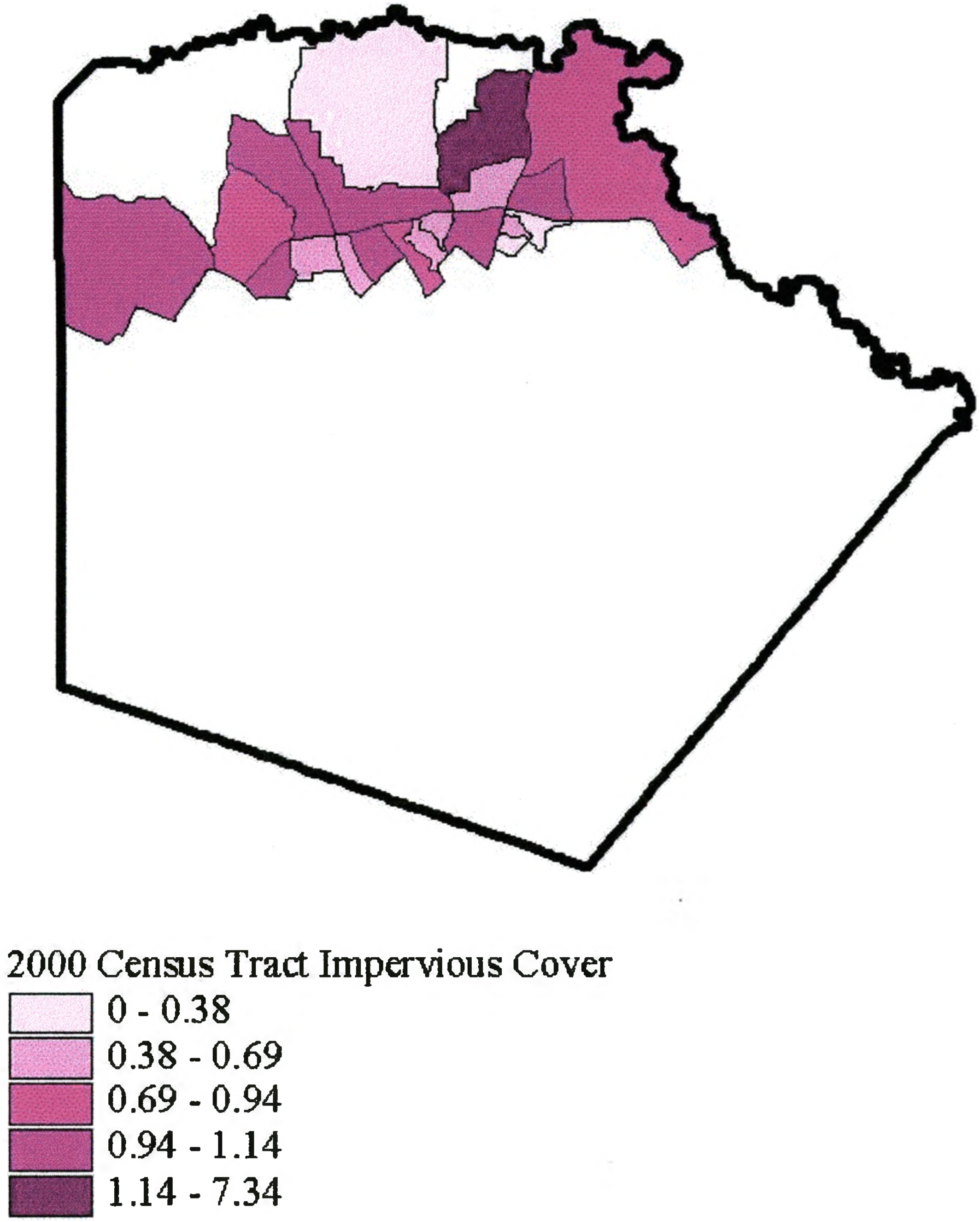

Fig. 13. 2000 Edwards Aquifer Census Tract Impervious Cover in Square Miles.

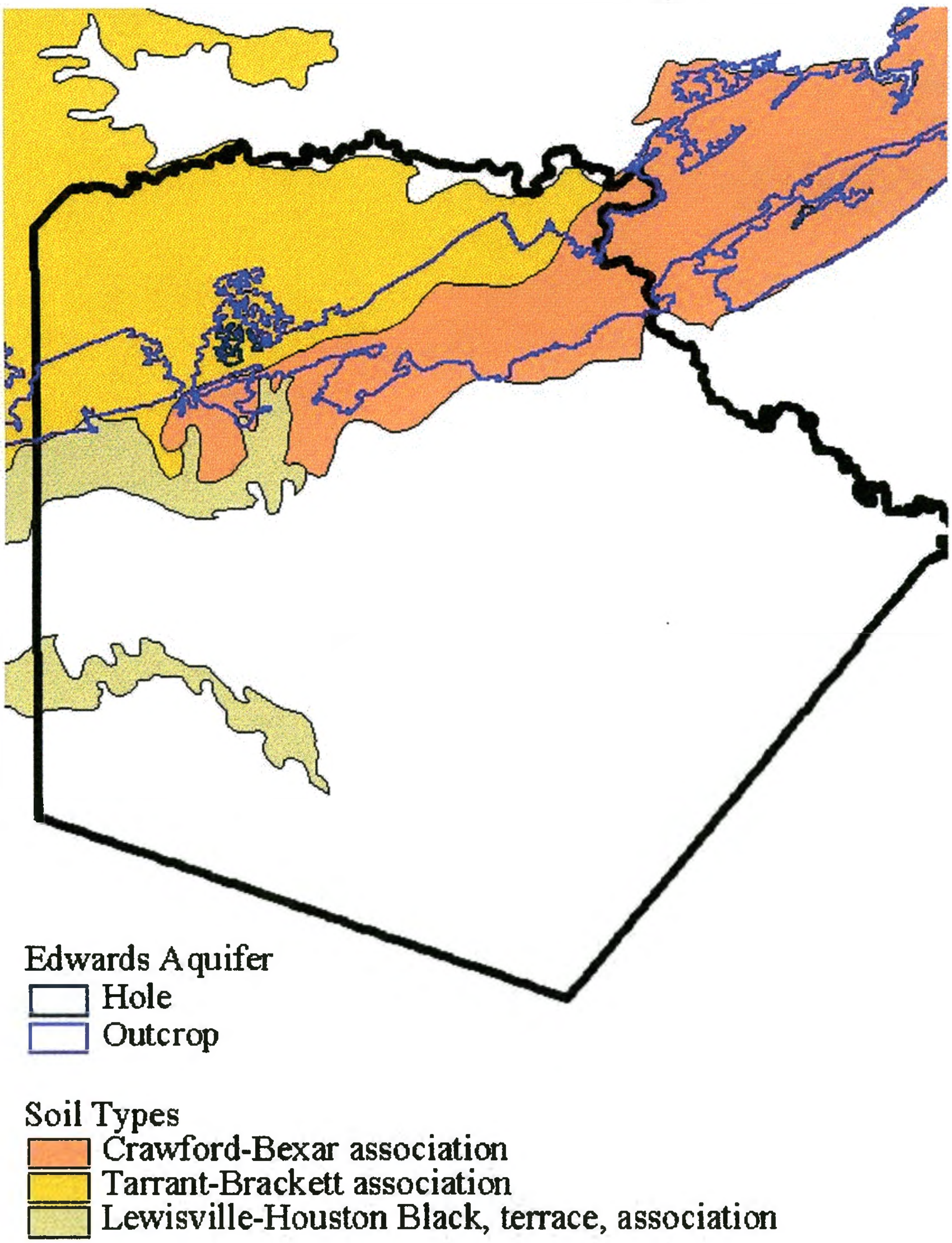

Fig. 14. Soil Types and Edwards Aquifer Recharge Zone
Bexar County, Texas.

belonging to the hydrologic soil group B with curve numbers based on the dominant land use, the TR-55 model was used to estimate runoff for each of the study years. Accumulated runoff was also calculated for 1980, 1990, and 2000 under 1970 conditions. Precipitation and runoff estimates are presented in Table 8. Runoff estimates were then converted into discharge amounts presented in Table 9.

Stream Recharge and In-situ Recharge Totals

Stream recharge was estimated based on runoff conditions produced under 1970 to 2000 land use conditions. Utilizing the relationships outlined by Leopold and Maddock (1953) in USGS Professional Paper 252, increases in streamflow caused by runoff and their effects on wetted perimeter were calculated and are presented in Table 10. Ratios between study year wetted perimeter and CN 82 (1970) wetted perimeter were used as weighting factors against USGS stream recharge amounts to calculate pre-urbanization streamflow. These results are presented in Table 11.

In-situ recharge was estimated based on the assumption that total in-situ recharge accounts for 20 percent of total potential recharge. Using the ratio of impervious cover for 1980, 1990, and 2000 to the base year of 1970 as a weighting factor against the amount of potential recharge, the amount of actual in-situ recharge was calculated. These calculations as well as the difference between recorded USGS estimates and calculated in-situ recharge based on land use and impervious cover are presented in Table 12.

Recorded stream recharge, in-situ recharge, and total recharge (Table 13) were compared with potential calculated values (Table 14) and differences are presented in Table 15.

Table 8
Precipitation and Runoff Estimates
1970-2000

Month	1970 Precipitation	1970-CN 82 Runoff
	inches	inches
January	1.10	0.15
Februray	2.66	1.12 .
March	1.98	0.63
April	1.13	0.16
May	7.30	5.19
June	0.89	0.08
July	0.91	0.08
August	0.95	0.10
September	4.35	2.50
October	1.31	0.25
November	0.01	0.10
December	0.15	0.04
Total	22.74	10.41

Month	1980 Precipitation	CN 82 Runoff	1980-CN 83 Runoff
	inches	inches	inches
January	0.72	0.03	0.04
Februray	0.74	0.04	0.05
March	0.98	0.11	0.12
April	1.67	0.44	0.48
May	6.42	4.37	4.48
June	0.52	0.00	0.01
July	0.26	0.02	0.01
August	2.64	1.10	1.16
September	5.05	3.12	3.22
October	1.09	0.15	0.17
November	3.53	1.80	1.88
December	0.61	0.01	0.02
Total	24.23	11.19	11.64

Table 8
Precipitation and Runoff Estimates
1970-2000

Month	1990 Precipitation	CN 82 Runoff	1990-CN 84 Runoff
	inches	inches	inches
January	1.17	0.18	0.23
Februray	2.68	1.13	1.26
March	5.17	3.23	3.43
April	4.52	2.65	2.84
May	3.28	1.60	1.75
June	1.18	0.19	0.24
July	8.29	6.13	6.38
August	1.30	0.24	0.30
September	3.70	1.95	2.11
October	3.71	1.95	2.12
November	3.11	1.46	1.61
December	0.20	0.03	0.02
Total	38.31	20.75	22.29

Month	2000 Precipitation	CN 82 Runoff	2000-CN 85 Runoff
	inches	inches	inches
January	1.61	0.41	0.53
Februray	2.25	0.82	0.99
March	1.02	0.12	0.18
April	1.54	0.37	0.48
May	3.96	2.17	2.43
June	7.32	5.21	5.56
July	0.19	0.03	0.02
August	0.18	0.03	0.02
September	2.77	1.20	1.40
October	6.56	4.50	4.84
November	8.90	6.71	7.09
December	2.04	0.67	0.83
Total	38.34	22.24	24.36

Table 9
Runoff Estimates Based on 1970 and Yearly Land Use Conditions

Year	1970 Runoff	1980 Runoff	1990 Runoff	2000 Runoff
	inches	inches	inches	inches
1970	10.41			
1980	11.19	11.64		
1990	20.75		22.29	
2000	22.24			24.36

Year	CN 82 Runoff	CN 83 Runoff	CN 84 Runoff	CN 85 Runoff
	cfs	cfs	cfs	cfs
1970	104.98			
1980	112.85	117.39		
1990	209.26		224.79	
2000	224.29			245.67

Sources: NOAA 1970; NOAA 1980; NOAA 1990; NOAA 2000; Soil Conservation Service 1984.

Table 10
Annual Streamflow and Wetted Perimeter
1970-2000

Year	CN 82 Runoff	Width	Depth	Wetted Perimeter
	cfs	ft	ft	ft
1970	104.98	114.02	0.61	115.24
1980	112.85	116.18	0.63	117.44
1990	209.26	136.41	0.81	138.02
2000	224.29	138.90	0.83	140.55

Year	Runoff	Width	Depth	Wetted Perimeter	Increase in Wetted Perimeter
	cfs	ft	ft	ft	percent
1970	104.98	114.02	0.61	115.24	-----
1980	117.39	117.38	0.64	118.66	1.04
1990	224.79	138.98	0.83	140.63	1.89
2000	245.67	142.22	0.86	143.94	2.41

Note: Figures based upon changes in channel geometry following methods of Leopold and Maddock (1953).

Table 11
Streamflow Recharge Amounts
1970-2000

Year	Stream Recharge	Increase in Wetted Perimeter	Pre-Urbanization Streamflow	Increase over 1970 Conditions
	acre-feet	percent	acre-feet	acre-feet
1970	55,040	-----	-----	-----
1980	15,040	1.04	14,890	150
1990	28,720	1.89	28,190	530
2000	22,880	2.41	22,340	540

Source: USGS 1970; USGS 1971; USGS 1980; USGS 1981; USGS 1990; USGS 1991; USGS 2000.
Note: Streamflow data is recorded in Water Years which run from October of one calendar year to September of the following calendar year.

Table 12
In-Situ Recharge Amounts
1970-2000

Year	Impervious Area	In-situ Recharge	Calculated In-situ Recharge	Difference
	% area	acre-feet	acre-feet	acre-feet
1970	1.44	13,760	-----	-----
1990	5.85	7,180	7,150	-30
2000	7.64	5,720	5,290	-430

Source: USGS 1970; USGS 1971; USGS 1980; USGS 1981; USGS 1990; USGS 1991; USGS 2000.
Note: Streamflow data is recorded in Water Years which run from October of one calendar year to September of the following calendar year.

Table 13
Edwards Aquifer Recharge
1970-2000

Year	Stream Recharge	In-situ Recharge	Recharge Total
	acre-feet	acre-feet	acre-feet
1970	55,040	13,760	68,800
1980	15,040	3,760	18,800
1990	28,720	7,180	35,900
2000	22,880	5,720	28,600

Source: USGS 1970; USGS 1971; USGS 1980; USGS 1981; USGS 1990; USGS 1991; USGS 2000.
Note: Streamflow data is recorded in Water Years which run from October of one calendar year to September of the following calendar year.

Table 14
Calculated Recharge
1970-2000

Year	Stream Recharge	In-situ Recharge	Recharge Total
	acre-feet	acre-feet	acre-feet
1970	55,040	-----	-----
1980	14,890	-----	-----
1990	28,190	7,150	35,340
2000	22,340	5,290	27,630

Table 15
Recharge Differences Due to Urbanization
1970-2000

Year	Stream Recharge	In-situ Recharge	Change	Percent Change
	acre-feet	acre-feet	acre-feet	
1970	0	-----	-----	-----
1980	+150	-----	-----	-----
1990	+530	-30	+500	+1.40
2000	+540	-430	+110	+0.38

CHAPTER 5

ANALYSIS OF RESULTS

The examination of the effects of development over the Edwards Aquifer on recharge in San Antonio/Bexar County is threefold and consists of the analysis of how changes in land use have affected impervious cover, how impervious cover has affected runoff, and how changes in stream and in-situ recharge affect total recharge amounts.

Changes in Land Use and Effects on Impervious Cover

The bifurcation of tracts over the past thirty years makes straight analysis of the change in impervious cover difficult. This problem is alleviated through comparison of total land area for all census tracts lying in the study area with total amounts of impervious cover of those census tracts (Table 11). Between 1970 and 1990, impervious cover over the recharge zone increased from 1.40 percent to 5.85 percent and between 1970 and 2000, impervious cover increased from 1.40 to 7.64 percent.

Changes in Impervious Cover and Effects on Runoff, Streamflow, and Stream Recharge

Runoff characteristics were based on the assumption that the soil characteristics in the study area belong to hydrologic soil group B and dominant land use of the study years. With curve numbers ranging from 82 to 85, the amount of direct runoff, in

Table 16
Total Census Tract Area and Total Impervious Cover

1970		
Census Tract	**Total Area**	**Total Imp.Cover**
	mi^2	**mi^2**
1211	22	0.32
1218	11	0.00
1219	58	0.00
1818/1819	35	0.96
1820	5	0.38
1821	5	0.33
1914	11	0.32
1915	7	0.34
1916	49	0.02
1917	6	0.64
1918	23.30	0.00
TOTAL	231.07	3.32
TOTAL PERCENT		1.40

Table 16
Total Census Tract Area and Total Impervious Cover

1990		
Census Tract	**Total Area**	**Total Imp.Cover**
	mi^2	**mi^2**
1211.06	3.20	0.72
1211.07	2.10	0.71
1219.01	52.00	0.43
1219.02	5.90	0.67
1818.01	2.65	0.38
1818.02	7.89	1.10
1818.05	5.50	0.97
1819	14.00	0.64
1820	14.90	0.66
1821	14.90	1.48
1914.01	4.00	0.66
1914.05	3.50	0.77
1915.01	4.20	0.67
1915.02	2.37	0.61
1916	48.90	0.00
1917	5.50	0.94
1918.01	2.81	0.52
1918.02	5.90	0.20
1918.03	14.60	0.42
TOTAL	214.82	12.56
TOTAL PERCENT		5.85

Table 16
Total Census Tract Area and Total Impervious Cover

2000		
Census Tract	**Total Area**	**Total Imp.Cover**
	mi^2	**mi^2**
1211.17	1.08	0.32
1211.18	2.10	0.56
1211.16	1.17	0.38
1219.01	52.00	0.80
1219.02	5.90	1.14
1818.01	2.65	0.65
1818.06	4.20	0.69
1818.12	4.05	1.11
1819	14.00	1.09
1820	14.90	0.94
1821.04	40.72	1.01
1914.05	3.50	0.84
1914.06	1.80	0.55
1914.07	2.27	0.65
1915.01	4.20	0.83
1916	48.90	0.00
1917	5.50	1.06
1918.02	5.90	0.74
1918.03	14.60	1.03
1918.05	55.27	7.34
TOTAL	284.71	21.75
TOTAL PERCENT		7.64

combination with amounts of impervious cover, were used to calculate increases in streamflow and the resulting increased wetted perimeter.

Streamflow is estimated to account for up to 80 percent of aquifer recharge, and one may assume that an increase in streamflow yields an increase in recharge. Wetted perimeter for the Salado Creek (Upper Station) increased 1.04 percent from 1970 to 1980 and 1.89 percent from 1970 to 1990. For the thirty year study period from 1970 to 2000, the wetted perimeter of Salado Creek increased 2.41 percent resulting in an increase of 540 acre-feet (664,000 m^3) of annual stream recharge.

Changes in Impervious Cover and Effects on Recharge

The official method for measuring recharge of the Edwards Aquifer uses a water-balance approach which does not include actual measurements of in-situ recharge nor account for land use. Although land use was not considered a significant factor in the 1970s, the turn of the century has been marked with a drastic change in distribution patterns of population and development.

Using amounts of impervious cover as weighting factors, in-situ recharge was calculated and compared with recorded values assumed to be 20 percent of total recharge. Impervious cover for the study year 1980 could not be calculated as a result of partial census counts, and hence in-situ recharge could not be calculated. The difference between recorded and calculated in-situ recharge in 1990 was estimated to be 30 acre-feet (37,000 m^3) and increased in 2000 to 430 acre-feet (530,000 m^3) of annual recharge lost to urbanization.

When increases in runoff and decreases of in-situ recharge due to increased impervious cover are considered, the net impact is a slight increase (less than two percent) in total recharge.

CHAPTER 6

CONCLUSIONS

The purpose of this study was to find out what relationship, if any, existed between development over the recharge zone of the Edwards Aquifer in San Antonio/Bexar County and recharge amounts. Between 1970 and 2000 impervious cover increased from 1.40 percent to 7.64 percent, which increased runoff and streamflow recharge and decreased the amount of in-situ recharge.

This study has shown that increases in urbanization result in slight increases in net recharge. This relationship is most evident in wetter years consistent with the hydrogeology of the Edwards Aquifer in which aquifer water levels, recharge, and springflow are closely related to precipitation, decreasing during times of low precipitation and increasing during times of high precipitation.

While methods of recharge enhancement are encouraged by the City of San Antonio, this type of recharge increase is coupled with serious problems. With the Edwards Aquifer being the primary source of water for the San Antonio/Bexar County region, protection of water quality is of primary importance. Runoff from impervious features such as parking lots may include the contaminants oil and gasoline which can pose serious threats to the aquifer.

The numbers produced in this study have certain inherent limitations based upon the need to make assumptions. The splitting of census tracts during the study period made it difficult to analyze the progression of impervious cover over the recharge zone during the past 30 years. Partial counts for census year 1980 resulted in the year's exclusion from the study. Second, for areas that are not gauged, estimated amounts of recharge are based on the assumption that the runoff characteristics are similar to runoff characteristics of the adjacent gaged areas. Since recharge data is estimated for the whole basin using runoff, rainfall, and total monthly flow at the Salado Creek station (08178700), a direct comparison of effects of impervious cover, runoff, and streamflow was impossible. Although runoff is accounted for in recharge estimates calculated by the USGS using methods presented by Puente in 1978, land use is not. In-situ recharge is merely estimated as a percent of the total.

The strain between human population growth and water resources is one that the San Antonio/Bexar County area is confronting. The water supply of the area is clouded by growing urban, energy, and industrial demands. The effects and processes of population growth and their subsequent effects on the availability of water resources are essential to understanding what needs to be changed, where, for what reasons, at what times, by whom, and for what purposes. Trends indicate future increased population growth and increased strain on already dramatically limited water resources. These trends imply increased consequences to the social, economic, political and natural environments of San Antonio/Bexar County.

REFERENCES

Anderson, Andrea. 1990. Neighbors: Suburban populations grow. *San Antonio Light*, 11 October, sec. H, p. 1.

Barton Springs/Edwards Aquifer Conservation District. n. d. About the aquifer: Three segments of the Edwards Aquifer. http://www.bseacd.org/aquifer.html; accessed 15 February 2001.

Bedient, Philip B., Charles J. Newell, and Handi S. Rifai. 1994. *Groundwater contamination: Transport and remediation.* Englewood Cliffs, NJ: PTR Prentice Hall.

Beekman, G. B., 1998. Water conservation, recycling and reuse. *International Journal of Water Resources Development* 14, no. 3: 353-364.

Bower, Tom. 1994. Aquifer recharge zone rules to impose sweeping change. *San Antonio Express-News*, 20 November, sec. 1A, p. 1, 12.

Bower, Tom, and Susie Phillips Gonzalez. 1995. Aquifer rules likely to pass easily: Council to vote on proposals. *San Antonio Express-News*, 12 January, sec. 1A, p. 1, 4.

Brown, Lester R. and Hal Kane. 1994. *Full house: Reassessing the Earth's population carrying capacity.* New York: W. W. Norton.

Bureau of the Census. U. S. Department of Commerce. 1970. *1970 census of population and housing. Census tracts, San Antonio, Tex. standard metropolitan statistical area.* U. S. Department of Commerce.

__________. 1980. *1980 census of population and housing. Census tracts, San Antonio, Tex. standard metropolitan statistical area.* U. S. Department of Commerce.

__________. 1990. *1990 census of population and housing. Census tracts, San Antonio, Tex. standard metropolitan statistical area.* U. S. Department of Commerce.

__________. 2000. *2000 census of population and housing.* http://www.census.gov/dmd/www/2khome.htm; accessed 29 October 2001.

Bush, Rudolph. 1999. Suburban sprawl: A creeping issue? Officials debate causes, solutions. *San Antonio Express-News*, 7 April, SA News Archives. http://www.mysanantonio.com/expressnews/; accessed 11 October 2001. Record number: 423607.

Campbell, Bernard. 1995. *Human ecology: The story of our place in nature from prehistory to the present.* New York: Aldine De Gruyter.

Cohen, J. 1995. *How many people can the Earth support?* New York: W. W. Norton.

Donahue, John M., and Barbara R. Johnston. 1998. *Water, culture, power: Local struggles in a global context.* Washington, D. C. : Island Press.

Eckhardt, Gregg A. n. d. a Edwards Aquifer homepage: Introduction to the Edwards Aquifer. http://www.edwardsaquifer.net/intro.html; accessed 7 March 2001.

__________. n. d. b Edwards Aquifer: Central section. http://edwardsaquifer.net/images.html; accessed 15 February 2001.

__________. n. d. c Cross section of the Edwards Aquifer. http://edwardsaquifer.net/images.html; accessed 15 February 2001.

Edwards, Thomas. 1997. Population growth moves north: Areas outside Loop 410, adjacent counties gaining new residents, housing. *San Antonio Express-News*, 2 February, sec. G, p. 2.

Edwards Aquifer Authority. 2000. *Hydrogeologic data report for 1999.* San Antonio, TX: Edwards Aquifer Authority.

Gardner, Gary. 1995. From oasis to mirage: The aquifers that won't replenish. *World Watch* 8, no. 3 (May/June): 30-6.

Gleick, P. H. 1989. Climate change, hydrology, and water resources. *Reviews of Geophysics* 27, issue 3: 329-44.

Goodland, R., H. H. Daly, and S. Serafy. 1992. *Population, technology, and lifestyle.* Washington, D. C. : Island Press.

Gunter, Pete A. Y., and Max Oelschlaeger. 1997. *Texas land ethics.* Austin, TX: University of Texas Press.

Hammond, Jr., Weldon. W. 1985. Regional hydrogeology of the Edwards Aquifer, south central Texas. In *Water resources symposium twelve. Issues in groundwater management: Austin, Texas*, ed. Smerdon, E.T. and W.R. Jordan, 53-68. Austin, TX: University of Texas, Center for Research in Water Resources.

Harper, Charles L. 1996. *Environment and society*. Upper Saddle River, NJ: Prentice Hall.

Hicks, Lesli. 1995. Growth to north more happenstance than plot. *San Antonio Express-News*, 28 May, sec. A, p. 16.

Holley, Joe. 2000. Water woes: Growth, drought put precious resource in jeopardy," *San Antonio Express-News*, 3 September, SA News Archives. http://www.mysanantonio.com/expressnews/; accessed 11 October 2001. Record number: 506762.

Jensen, Ric. 1996. Why droughts plague Texas. *Texas Water Resources* 22, no. 2 (Summer). http://twri.tamu.edu/twripubs/WtrResrc/v22n2.html; accessed 29 January 2001.

Jennings, Marshall E., Peter W. Bush, and Greg M. Nalley. 1992. Generalized hydrologic characteristics of the Edwards Aquifer. In *American Water Resources Association, Texas section, fall meeting*, ed. American Water Resources Association, 19-26. American Water Resources Association.

Kaczmarek, Zdzislaw, Nigel W. Arnell, and Leszek Starkel. 1996. Climate, hydrology, and water resources. In *Water resources management in the face of climatic/hydrologic uncertainities,* ed. Kaczmarek, Zdzislaw, Kenneth M. Strzepek, Laszlo Somlyody, and Valentina Priazhinskaya, 3-29. Dordecht, Netherlands: Kluwer Academic Publishers.

Leopold, L. M. and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. U. S. Geological Survey Professional Paper 252. Washington, D. C. : U. S. Geological Survey.

Leopold, Luna B. 1997. *Water, rivers, and creeks*. Sausalito, CA: University Science Books.

Maclay, R. W. 1989. Edwards Aquifer in the San Antonio Region: Its hydrology and management. *South Texas Geological Society Bulletin* 30, no. 4:11-28.

__________. 1995. *Geology and hydrology of the Edwards Aquifer in the San Antonio area, Texas*. U. S. Geological Survey Water Resources Investigations Report 95-4186. Austin, TX: U. S. Geological Survey.

Marsh, William M. 1997. *Landscape planning: Environmental applications*. New York: John Wiley and Sons.

Marsh, William M., and Nina L. Marsh. 1994. Microtopography, runoff processes, sediment transport, and their implications for land use planning in the central Texas Hill Country. In F*orty Fourth Annual Convention of the Gulf Coast Association of Geological Societies*, ed. Gulf Coast Association of Geological Societies, 447-456. New Orleans, LA: Gulf Coast Association of Geological Societies.

National Oceanic and Atmospheric Administration (NOAA). 1970. *Climatological data annual summary: Texas*. Vol 75, no 13. U. S. Department of Commerce.

__________. 1980. *Climatological data annual summary: Texas*. Vol 85, no 13. U. S. Department of Commerce.

__________. 1990. *Climatological data annual summary: Texas*. Vol 95, no 13. U. S. Department of Commerce.

__________. 2000. *Climatological data annual summary: Texas*. Vol 105, no 13. U. S. Department of Commerce.

Needham, Jerry. 1995. Surburban sprawl muddies same waters that once spurred Growth. *San Antonio Express-News*, 28 May, sec. A, p. 17.

__________. 1998. Tougher aquifer restrictions oked. *San Antonio Express-News*, 24 September, sec. 1B, p. 3.

North, Gerald R., George Bomar, John Griffiths, James Norwine, Juan B. Baldes. 1995. The Changing Climate of Texas. In *The Impact of Global Warming on Texas*, ed. Gerald R. North, Jurgen Schmandt, Judith Clarkson, 24-49. Austin, TX: The University of Texas Press.

Peet, John. 1992. *Energy and the ecological economics of sustainability*. Washington, D. C. : Island Press.

Pimentel, David, James Houser, and Erika Preiss. 1997. Water resources: Agriculture, the environment, and society. *Bioscience* 47 (February): 97-106.

Postel, Sandra L. 1986. Needed: A new water policy. *Challenge!* 26, no. 6 (January/February): 43-9.

__________. 1992. *Last oasis: Facing water scarcity*. New York: W. W. Norton.

__________. 1999. When the world's wells run dry. *World Watch* 12, no. 5 (September/October): 97-106.

Puente, Celeso. 1978. Method of estimating natural recharge to the Edwards Aquifer in the San Antonio area, Texas. Water-Resources Investigation 78-10. Austin, TX: U. S. Geological Survey.

Robins, N.S. 1998. *Groundwater pollution, aquifer recharge, and vulnerability.* London: Geological Society of London.

Rose, Peter R. 1994. Historical rainfall cycles and the Edwards Aquifer: An unfolding tragedy of the commons in south Texas. *Bulletin of the South Texas Geological Society* 35, no. 2: 8-9.

San Antonio Water System. 1998. *San Antonio Water System water resource plan: Securing our water future together.* San Antonio, TX: San Antonio Water System.

__________. 2000. *Water statistics-1999.* San Antonio, TX: San Antonio Water System.

San Antonio Water System Source Water Watershed Protection. n. d. Edwards Aquifer recharge and transition zone in Bexar county. http://www.saws.org/functions/source_water_watershed_protection/Aquifer%20Protection/index.shtml; accessed 15 February 2001.

Sharp, John M., and Jay L. Banner. 1997. The Edwards Aquifer: A resource in conflict. *GSA Today* 7, no. 8: 1-8.

__________. 2000. The Edwards Aquifer: Water for thirsty Texans. In *Geology's gaze: paths to sustainable existence,* ed. Schneiderman, J.S., 154-165. New York, NY: W. H. Freeman.

Sheridan, David. 1981. The unwatered west. *Environment* 23, no. 2 (March): 7-13, 38-40.

Slade, Jr., Ramond M. 1984. Hydrogeology of the Edwards Aquifer-Barton Springs segment, Travis and Hays counties, Texas. Guidebook 6. Austin, TX: U. S. Geological Survey.

Soil Conservation Service. 1962. *Soil survey: Bexar county Texas.* U. S. Department of Agriculture.

__________. 1972. *National engineering handbook, section 4, hydrology.* Washington, D. C. : U. S. Department of Agriculture.

__________. 1984. *Engineering field manual.* Washington, D. C. : U. S. Department of Agriculture.

Stankowski, Stephen J. 1972. Population density as an indirect indicator of urban and suburban land-surface modifications. United States Geological Survey Professional Paper 800-B, B219-B224. Washington, D. C. : U. S. Geological Survey.

Stein, William G., and George B. Ozuna. 1998. Geologic framework and hydrogeologic characteristics of the Edwards Aquifer recharge zone, Bexar county, Texas. *South Texas Geological Society Bulletin* 39, no.3:9-16.

Tackett, John. 1994. Applewhite plan stirs debate. *San Antonio Express-News*, 24 July, SA News Archives. http://www.mysanantonio.com/expressnews/; accessed 30 January 2001. Record number: SAEN59947.

Texas Natural Resource Conservation Commission (TNRCC). 1999a. *Complying with the Edwards Aquifer rules: Administrative guidance.* Austin, TX: Texas Natural Resource Conservation Commission.

__________. 1999b. Edwards Aquifer rules. 30 TAC Chapter 213.

Texas Water Development Board (TWDB). 1997. *Water for Texas: A consensus-based update to the state water plan.* Document GP-6-1. Austin, TX: Texas Water Development Board.

U. S. Geological Survey (USGS). U. S. Department of the Interior. 1970. *Water resources data, Texas, water year 1970.* Part 1. Austin, Texas: U. S. Geological Survey.

__________. 1971. *Water resources data, Texas, water year 1971.* Part 1. Austin, Texas: U. S. Geological Survey.

__________. 1980. *Water resources data, Texas, water year 1980.* Volume 3. Austin, Texas: U. S. Geological Survey.

__________. 1981. *Water resources data, Texas, water year 1981.* Volume 3. Austin, Texas: U. S. Geological Survey.

__________. 1990. *Water resources data, Texas, water year 1990.* Volume 3. Austin, Texas: U. S. Geological Survey.

__________. 1991. *Water resources data, Texas, water year 1991.* Volume 3. Austin, Texas: U. S. Geological Survey.

__________. 2000. *Water resources data, Texas, water year 2000.* Volume 5. Austin, Texas: U. S. Geological Survey.

Ward, Andy, and William Elliot (eds). 1995. *Environmental hydrology.* Boca Raton, LA: Lewis Publishers.

Williams, Joel. 1995a. Push to the north changes face of city. *San Antonio Express-News*, 28 May, sec. A, p. 1 and 19.

__________. 1995b. Alamo city now no. 9 in population. *San Antonio Express-News*, 28 October, SA News Archives. http://www.mysanantonio.com/expressnews/; accessed 30 January 2001. Record number: SAEN121304.

__________. 1996. Rural areas growing like weeds. *San Antonio Express-News*, 9 March, sec. A, p. 1 and 7.

Winter, Thomas C. 1995. Landscape approach to identifying environments where groundwater and surface water are closely interrelated. In *Groundwater management: Proceedings from the international symposium sponsored by the Water Resources Engineering Division, American Society of Civil Engineers, in conjunction with the ASCE's first international conference on water resources engineering in San Antonio, Texas,* ed. Charbeneau, Randell J., 139-144. New York: American Society of Civil Engineers.

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