Technical Report

CRWR 244

# Management of The Edwards Aquifer: A Critical Assessment

by


Daene C. McKinney
Assistant Professor

and

David W. Watkins, Jr.
Research Assistant


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Bureau of Engineering Research • The University of Texas at Austin
Balcones Research Center • Austin, TX 78712

# ABSTRACT

The Edwards aquifer is a tremendous resource for Central Texas. The aquifer is the sole source of water for the City of San Antonio, supplies spring flows which support a number of endangered species as well as a large recreation industry, and provides water to many farmers and ranchers. Despite the aquifer's vast storage capacity and transmissive capabilities, average annual pumping is now exceeding average annual recharge, and the next drought could result in great economic and environmental hardship.

In an attempt to mitigate these potential hardships, and prevent federal intervention under the Endangered Species Act, the Texas Water Commission (TWC) has proposed an interim management plan for the aquifer. This plan includes economic incentives to reduce pumping, as well as mandatory curtailments to come into effect during a drought, so that a minimum acceptable flow may be maintained in Comal Springs. The TWC had hoped that the plan would be agreeable to all the affected parties, but this has not been the case.

The purpose of this report is to evaluate the proposed interim management plan according to the following criteria: (1) Are the legal, economic, and environmental bases for the plan accurate and reliable? (2) What is the likelihood and severity of potential impacts of the plan? and (3) Should adjustments be made to the plan, or should other issues be addressed by the plan? To provide a thorough evaluation in this context, the report is divided into four main chapters: legal, economic, environmental, and groundwater simulation.

Chapter 2 discusses the legal issues which pertain to the proposed management plan. It includes a discussion of current Texas groundwater law and a comparison to the laws of other western states. State-wide issues, such as options for the Texas State Legislature, and local issues, such as the roles of water conservation districts, are reviewed. Finally, a summary and analysis of the lawsuit by the Sierra Club against the U.S. Fish and Wildlife Service is presented. The section concludes that, unless all affected parties can agree to a management plan, the State Legislature must act to prevent federal intervention and to protect the resource.

Chapter 3 highlights the economic importance of the Edwards aquifer. With population in the area projected to increase significantly, the region will become even more dependent on the Edwards aquifer unless new water supply sources are brought on

line. The economic feasibility of some alternative water sources, along with the economic impacts of pumping curtailment, is discussed. One conclusion is that economic (i.e., a market-based system) incentives are preferable to mandatory pumping restrictions.

Chapter 4 provides an overview of the many complex hydrological and environmental interactions which must be considered in managing the Edwards aquifer. A brief discussion of the hydrogeology of the aquifer is given, followed by the identification of the flora and fauna which rely on spring flows from the aquifer. The dependence of biota in the bays and estuaries on spring flows is documented.

Chapter 5 evaluates the groundwater simulation models used by the TWC for development and assessment of the management plan. The accuracy and reliability of these models is assessed, and these models are compared to other existing models in terms of complexity and technical plausibility. The limitations of regional models are pointed out, and it is recommended that the TWC use the most accurate and reliable model available.

Chapter 6 presents some general conclusions and recommendations, as follows: (1) A management plan is definitely needed for the Edwards aquifer, and the TWC's proposed plan is a step in the right direction. (2) Due to the disagreement among parties affected by the plan, however, legislative action is required to prevent federal intervention. (3) Whatever plan is adopted, it should include a market-based scheme for water conservation, recommendations for alternative water supply sources, and provisions for minimum daily flows in the springs. (4) The most accurate hydrological model available should be used in developing and evaluating the plan, and the limitations of the model should be considered.

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# 1.0 INTRODUCTION

In April 1992, the Texas Water Commission (TWC) proposed a management plan for the Edwards aquifer [TWC, 1992]. This plan is just one of many attempts to manage, or at least make recommendations regarding, the Edwards aquifer [EARDC, 1981; EUWD, 1987; GBRA, 1988]. The Edwards aquifer is an extremely valuable resource because it is the sole source of water for millions of people and thousands of businesses and farms in the region, and it also supplies several springs and associated areas in which endangered species of plants and animals live (Figure 1.1) [TWC, 1991].

It is likely that the TWC management plan was an attempt to prevent federal intervention under the Endangered Species Act. As discussed below, the Sierra Club has sued the U.S. Fish and Wildlife Service (USFWS) for failure to protect the endangered species associated with Comal and San Marcos Springs, which issue from the Edwards aquifer. The ultimate outcome of this lawsuit remains to be seen, but it may result in federal management of pumping from the Edwards aquifer. Important elements of the management plan include:

(1) The acceptance of an interim springflow criterium of 100 cfs at Comal Springs 80% of the time except during severe drought;

(2) An aggressive water conservation program, including economic incentives, to reduce annual pumping from the aquifer 538,000 to 440,000 acre-feet per year (AF/yr);

(3) A regional drought management plan, involving mandatory pumping curtailments;

(4) Financial support for a springflow augmentation feasibility study; and

(5) Support for the development of a comprehensive, long-term regional management plan.

The purpose of this report is to evaluate the TWC management plan with three primary objectives in mind:

(1) Evaluate the accuracy, reliability, and technical plausibility of the plan;

(2) Assess the likelihood and severity of potential economic and environmental impacts of the plan; and

(3) If possible, recommend improvements to the plan.

To provide a thorough and objective evaluation, the report encompasses four main chapters, each focusing on a different issue or area: (1) law and institutions, (2) economics and development, (3) ecology and the environment, and (4) hydrologic modeling and simulation. It is hoped that such an interdisciplinary evaluation will provide some insight as to how to manage the invaluable yet highly controversial Edwards aquifer.

Chapter 2 discusses the legal issues which pertain to the proposed management plan. It includes a discussion of current Texas groundwater law and a comparison to the laws of other western states. State-wide issues, such as options for the Texas State Legislature, and local issues, such as the roles of water conservation districts, are reviewed. Finally, a summary and analysis of the lawsuit by the Sierra Club against the Fish and Wildlife Service is presented. The section concludes that, unless all affected parties can agree to a management plan, the State Legislature must act to prevent federal intervention and to protect the resource.

Chapter 3 highlights the economic importance of the Edwards aquifer. With population in the area projected to increase significantly, the region will become even more dependent on the Edwards aquifer unless new water supply sources are brought on line. The economic feasibility of some alternative water sources, along with the economic impacts of pumping curtailment, are discussed. One conclusion is that economic incentives (i.e., a market-based system) are preferable to mandatory pumping restrictions.

Chapter 4 provides an overview of the many complex hydrological and environmental interactions which must be considered in managing the Edwards aquifer. A brief discussion of the hydrogeology of the aquifer is given, followed by the identification of the flora and fauna which rely on springflows from the aquifer. The dependence of biota in the bays and estuaries on springflows is documented.

Chapter 5 evaluates the groundwater simulation models used by the TWC for development and assessment of the management plan. The accuracy and reliability of these models is assessed, and these models are compared to other existing models in terms of complexity and technical plausibility. The limitations of regional models are pointed out, and it is recommended that the TWC use the most accurate and reliable model available.

Finally, Chapter 6 presents some conclusions and recommendations resulting from the study.

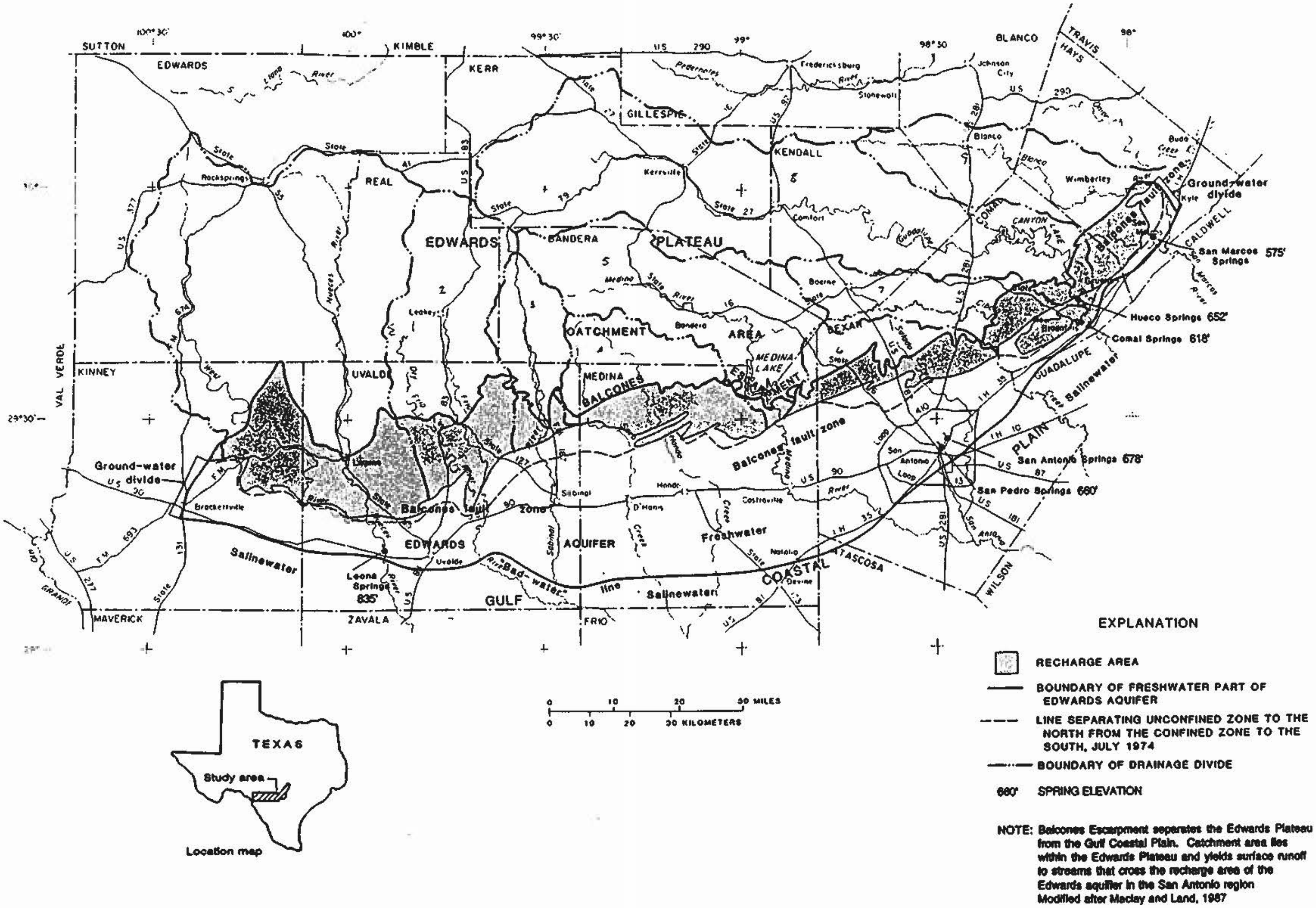



**Figure 1.1** Location and Extent of the Edwards (Balcones Fault Zone) Aquifer, San Antonio region [TWC, 1991].

# 2.0 LEGAL ISSUES

James M. Conroy, Julia E. A. Coonrod, Mathew D. Travers,
Daene C. McKinney, and David W. Watkins, Jr.

## 2.1 INTRODUCTION

In this chapter, the Texas Water Commission (TWC)-proposed management plan for the Edwards aquifer [TWC, 1992] is examined in light of legal issues affecting the plan. These issues include the possible legal bases for implementing the plan, the politics of various parties affected by the plan, and the ongoing lawsuits associated with management of the aquifer. Under current interpretation of Texas water laws, the State has no authority to regulate groundwater withdrawals, and therefore the TWC is prohibited from initiating the plan.

No matter how many studies are conducted for managing the Edwards aquifer, it is unlikely any management will actually occur without some type of legal action. Representatives from federal, state, and local levels are all involved in water law. At the federal level, the protection of water is shared by the Department of Agriculture, the Department of the Interior, the Department of Commerce, and the Environmental Protection Agency. At the state level, the Texas Water Commission has the primary responsibility for protecting the quality and quantity of Texas' water resources. At the local level, river authorities and local water suppliers are involved in local water supply and distribution, and underground water districts are involved with protection of water quality and quantity in aquifers. Players at all three levels are in some way currently involved with management issues of the Edwards aquifer.

The Edwards aquifer is a tremendous natural resource providing the sole source of water for the City of San Antonio, supplying springflows that provide a large recreation industry for the cities of New Braunfels and San Marcos, and providing water for numerous ranchers and farmers. Though the Edwards aquifer has been called "the lifeline of 15 Texas counties" [Jordan, 1992], the TWC plan is the most serious attempt to manage this important resource. However, it is questioned whether the Texas Water Commission currently has the legal authority to implement the plan. If the State is unsuccessful in implementing some type of management plan, it is very likely that the federal government will intervene. The federal government has the authority under the Endangered Species Act to protect endangered species in the aquifer, which could lead to federally mandated pumping limitations. To ensure Texas' authority in managing the aquifer, new state legislation is needed.

## 2.2 THE PLAN

The stated purpose of the TWC plan [TWC, 1992] is "to protect the water quality of the Edwards Aquifer Underground River; protect the water quality of the surface streams to which the Edwards Aquifer Underground River provides a significant springflow; achieve water conservation; maximize the beneficial use of water available for diversion from the underground river; protect springflow necessary for the maintenance of aquatic and wildlife habitat; protect the public health, safety, and welfare; and provide for instream uses and bays and estuaries." To accomplish these goals, the plan sets limits on total diversions from the Edwards aquifer and establishes procedures for persons wishing to divert such water.

The major problems associated with Texas groundwater management and water law are groundwater mining, waste of water, interference between wells, the inability to transfer groundwater rights, and a failure to recognize the link between surface and underground water [Smith, 1986]. The plan explicitly addresses four of these issues, with well interference the only issue not specifically addressed.

Groundwater mining, which is removal of water in excess of the recharge rate, is addressed by limiting removals to 450,000 acre-feet annually. This quantity exceeds the average annual recharge of the Edwards aquifer, and therefore, the plan would reduce withdrawal to 400,000 acre-feet by the year 2008. There are provisions in the plan to allow more water to be withdrawn on an interruptible basis if recharge is higher than normal. Also, pumping could be further restricted if recharge rates fall below normal in a drought period.

Waste of water would be stopped by direct control and by regulating who can pump from the Edwards aquifer. A "right of diversion" would be based on a person's need and purpose of use, historical use, and potential for reduction and elimination of waste through the use of reasonable conservation and reuse measures. The total amount of water available for use from the Edwards aquifer would also be a factor. Contractual sales and transfer of water rights would require TWC approval and would be subject to water conservation restrictions. Other states have used the ability to transfer water rights to allow cities to buy the water rights of agricultural users within the same aquifer to increase their allowable pumping. A case in point may be the catfish farmer who began pumping 45 million gallons per day from the Edwards aquifer in March 1991. He could possibly establish a historical usage or water right prior to the adoption of the new rules and later sell his water rights to San Antonio.

## 2.3 TEXAS GROUNDWATER LAW

There is no doubt that current groundwater law in the State of Texas is one of the largest stumbling blocks in managing the Edwards aquifer. Although all other western states have established more progressive groundwater laws, the State of Texas' courts have upheld the English common law rule of absolute ownership. The Texas Legislature has not modified this common law rule. The common law rule, based on an 1843 English Court decision [Acton vs Blundell, 1843] and sometimes called the "right of capture," gives a landowner the right to take for use or sale all the water that he can capture from below his land. At the time the rule was established, groundwater was thought to be completely unrelated to surface water. Although it is common knowledge today that groundwater is an interactive component of the hydrologic cycle just as is surface water, Texas laws continue to treat groundwater and surface water as totally separate, unrelated entities.

The interaction between ground and surface water is the driving force for implementation of a management plan for the Edwards aquifer. The protection of springflows at Comal and San Marcos Springs provides a critical incentive for managing the aquifer. Legal recognition of the interaction between ground and surface water is the basis for an integrated approach to water management within the Edwards aquifer "basin."

It is not surprising that this archaic notion of groundwater rights is the source of large controversy. By virtue of land ownership, Texans hold the rights to all underlying groundwater and virtually unlimited pumpage [Norris, 1990]. The only stipulation is that the water must be put to beneficial use, which begs the question, "What is beneficial use?"

In the past, Texas courts have been extremely flexible in their consideration of beneficial groundwater uses. Consequently, most uses were considered beneficial, and Texans have become accustomed to very little or no restrictions on their groundwater consumption. Even when the Legislature has attempted to restrict the use of groundwater by claiming control of subterranean streams, the courts have not obliged. The Texas Supreme Court has created a judicial presumption that all groundwater is percolating rather then free flowing and, therefore, the property of the land owners [Norris, 1990]. Exacting standards must be met to prove groundwater as other than percolating. Given all these problems with groundwater regulation and the fact that the English Rule's time has probably come and gone, options to reform the groundwater law of the State of Texas should be reviewed.

## 2.4 OTHER STATES

Almost every western state has a groundwater regulation system in place based on laws that differ from Texas' laws. California, Arizona, and New Mexico groundwater laws represent a full range of alternatives available. While other states have developed different systems, it is interesting to see how these states have attempted to settle their problems and compare them to Texas.

California has adopted the Correlative Rights Doctrine. This means property owners retain to the rights to groundwater under their land, but its use is subject to need and to the rights of adjacent land owners [Ventruizen, 1990]. The state does not intervene in conflicts as a regulatory agency. All disputes are settled privately in court. As long as the interested parties remain fairly objective, this system works well. However, California has had a lot of trouble with lawsuits between adjacent land owners, particularly in the arid agricultural regions in the south [Ventruizen, 1990]. In practice, this doctrine has not worked very well and has served to create a backlog of court cases.

The Reasonable Rule or American Rule is in effect in Arizona. This doctrine states that landowners still own the groundwater under their land, but pumpage limits are imposed and only a beneficial quantity can be used [Ventruizen, 1990]. Arizona determines the limits and beneficial uses at the state level and issues permits to prospective water users. A grandfather clause exists for past uses subject to state scrutiny. Most importantly, Arizona law provides for both civil and criminal penalties for abuses and a state agency to enforce them [Ventruizen, 1990]. In practice, this system has worked very well by providing flexibility and enforcement capability to the state.

New Mexico has taken a third approach to controlling its groundwater. The state adheres to the doctrine of Prior Appropriation. This means first come, first served, but it assumes the state was the very first, so that permits must be obtained from a state agency prior to groundwater use [Ventruizen, 1990]. In effect, New Mexico has taken all rights to groundwater away from land owners and has placed them in control of the state. If a prospective user can show the state that the water will be put to a good use, and there is water available, then a permit can be issued.

These three states have attempted to solve their groundwater management problems using doctrines that vary from almost no regulation in California to virtual totalitarian control in New Mexico. Arizona has set a good example, providing for both flexibility and regulation. Texas does not have to go far to see modern groundwater laws, based on 20th century knowledge, that work.

## 2.5 LEGAL BASES FOR THE PLAN

Texas law recognizes four distinct classes of water: (1) natural surface water, (2) diffused surface water, (3) percolating groundwaters, and (4) underground streams [Kaiser, 1987]. The classification of water that the Edwards aquifer falls into is subject to debate and has a tremendous impact on giving the State authority to implement the plan. Surface water found in water courses is owned by the State, which allows for planning and management of surface water systems. Underground "streams" are also owned by the State; however, designating a resource as an underground stream—as opposed to percolating groundwaters—is not as clear or obvious as designating it as surface water. Although the State does not manage groundwater, approximately 60% of the water used in the state is supplied by seven major and sixteen minor aquifers [Kaiser, 1987]. Ninety percent of Texas groundwater is in the Ogallala aquifer. The Ogallala aquifer is mentioned because parties interested in keeping the State from managing groundwater in the Ogallala aquifer are apparently quite politically influential.

In Texas, underground streams or rivers have been excluded from the definition of underground water [Texas Water Code §52.001]. But if an aquifer were to be judged an underground river, it would be subject to state control. However, in order to manage the Edwards aquifer through this mechanism, a state court must hold that the Edwards aquifer actually is an underground stream. In 1992, after an interpretation of state law by the Attorney General that the Edwards aquifer is an underground river, the Texas Water Commission attempted to seize control of the Edwards aquifer. However, State District Judge Lowrey ruled that the Legislature's intent in the Texas Water Code was that the Edwards aquifer be treated as percolating groundwater and not as an underground river. The TWC is appealing this decision.

The TWC is authorized to "make and enforce rules and regulations for conserving, protecting, preserving, and distributing underground, subterranean, and percolating water" and "to do all things necessary" for those purposes [Texas Water Code §28.011]. If the TWC attempts to manage the aquifer by the authority given them in §28.011, lawsuits addressing the constitutional validity of that statute are sure to arise. The volatility of this issue is evidenced by the Attorney General's reversal of opinion on the issue. In November 1991, the Attorney General's opinion upheld the constitutional validity of the statute; however, in March 1992, the Attorney General reversed this finding and found that his recent previous opinion had been misinterpreted by the TWC.

## 2.6 UNDERGROUND WATER DISTRICTS

The Texas Legislature authorized the creation of underground water conservation districts in 1949 and in 1985. Local voter approval is required to form a district. The 1985 legislation includes a provision for the TWC to initiate the formation of a district in an area if it is designated as a critical groundwater area. However, voters still have the ultimate say, having the power to veto the formation of a proposed district. These districts generally have the authority to promulgate rules for conserving, protecting, recharging, and preventing waste of underground water [Texas Water Code, Chapter 52]. Districts can require permits for new wells; however, the Edwards Underground Water District (EUWD) does not currently enforce the requirement of such permits.

Because of disagreements between the affected parties, the EUWD has been unsuccessful in promoting any type of management of the aquifer. In contrast, the High Plains Underground Water District has been successful in some management practices of the Ogallala aquifer, resulting in dramatic cutbacks in the use of irrigation water and a substantial increase in water levels. The success of this district explains its opposition to State authority over their principal water supply. If the EUWD had cooperation from all parties, then legislation would not be as vital to management of the aquifer. Unfortunately, because they felt their best interests (agricultural) were not being properly pursued, the counties of Uvalde and Medina have gone so far as to pull out of the district.

## 2.7 LOCAL ISSUES

The legal stalemate that surrounds the Edwards aquifer management plan is felt no more acutely than by the boards, committees, and individual citizens at the regional and local level. These are the people whose livelihoods are directly affected by the welfare of the aquifer. Yet, it is precisely these groups of people that have worked at cross purposes to each other to help create the situation that exists today. Part of the problem has been a complete refusal to compromise by some groups in the region, as is evidenced by the lack of participation in a single underground "super district." Another part of the problem has been the frustration of people who realize they have no authority to fix the problematic issues that afflict management of the aquifer. However, beyond all the conflict at this level, certain measures have been enacted to help conserve water, and many tentative plans for the future are being developed.

Perhaps the best way to analyze the issue is to break it down into interest groups. There are a number of major players involved. As previously mentioned, the EUWD is a state-mandated committee with regionally appointed board members that has limited supervisory powers. The City of San Antonio is the major municipal water consumer in the area, with responsibilities to its citizens, businesses, and future growth potential. The city has legal powers limited to local water consumption regulations. The agricultural interests in the region form a powerful lobby group that have made their demands clear. Also, the Guadalupe-Blanco River Authority (GBRA) is primarily trying to protect its interests in maintaining its water rights as downstream users of water from the aquifer.

Insight to these complex local issues—and their relation to the federal Endangered Species Act—is also gained by examining the lawsuit brought by the Sierra Club against the U.S. Fish and Wildlife Service (USFWS) in District Court [Sierra Club vs USFWS]. This suit was filed as an attempt to gain protection for several endangered and threatened species which reside within the Edwards aquifer, Comal Springs, and San Marcos Springs. The Sierra Club argued that the USFWS has not complied with the Endangered Species Act by failing to provide for the protection and recovery of these endangered and threatened (listed) species living in or near the springs. The Sierra Club also claimed that by failing to act to conserve the critical habitat of these species, the USFWS further harmed the species and jeopardized their very existence. The lawsuit, pertinent case law, and the federal ruling will be discussed in more detail in the next chapter.

### 2.7.1 The Edwards Aquifer Underground Water District

Due to Texas groundwater legislation, the EUWD is limited to a supervisory role in the region and can only enforce regulations during drought conditions. Accordingly, they have developed a drought management plan that strictly regulates water use during critical times. To date, however, they have not exercised their enforcement powers, and they have no authority to regulate water consumption during more plentiful periods. The EUWD has lobbied the Texas Legislature for more comprehensive powers over the region. Additionally, they have proposed a new drought management plan that compares aquifer water levels with demand and uses a graduated percent reduction not to exceed a 30% cumulative reduction in use. During extreme situations where human health and welfare are involved, the board would determine a revised crisis plan based on the needs at that time. This arrangement will be effective during droughts, but it does not address the basic problem of full time management of the aquifer.

The EUWD was also actively involved in the Sierra Club vs USFWS lawsuit. The EUWD was granted official status in the case as *amici curiae*, friend of the court. This gave the EUWD not only the right to introduce evidence during the proceedings but also the opportunity to cross-examine both the plaintiffs and the defendants in the case. It is understood that the EUWD's position in the case was essentially neutral. The group's sole desire is that the best interests of the aquifer and the people of the region are met by the courts' decision [Caroline Eagle, EUWD, personal communication, 1992].

Additionally, the EUWD has done its best to intervene in the establishment of local ordinances to conserve water. For instance, the EUWD pushed the city of San Antonio to pass several water conservation measures [Russell Masters, EUWD, personal communication, 1992]. Although they have no legal authority to create or regulate these measures, they have been able to operate as an effective lobby group in the region.

The EUWD has been undermined in its attempts to manage the aquifer by its lack of authority. The counties of Uvalde and Medina have pulled out of the district, as is their right. These two counties are the primary agricultural areas in the region and they believe their needs are not being met by the EUWD. They have formed autonomous water districts and have decided to take care of themselves using existing Texas groundwater law [Caroline Eagle, EUWD, personal communication, 1992]. EUWD recognizes Uvalde and Medina Counties' concerns and is trying to work with them in a spirit of cooperation [Russell Masters, EUWD, personal communication, 1992]. However, nothing more can be done at this level unless the Texas Legislature grants more comprehensive powers to the EUWD or unless all parties affected by management of the aquifer are cooperative.

### 2.7.2 San Antonio

The City of San Antonio is limited in its ability to regulate water use and manage the Edwards aquifer. The city has enacted some of the most demanding water conservation ordinances in the country, but beyond local laws the city is limited in its legal powers. Certainly, some new ordinances have been instituted in response to pressure from the EUWD and other groups like the Sierra Club, but the city recognizes its responsibility to both its inhabitants and to the future. The city has a year-round lawn watering ordinance that prohibits watering of lawns between 8 a.m. and 10 p.m. Additionally, all landscaping must be done with indigenous and water efficient foliage. Building codes stipulate that all new plumbing fixtures must be water efficient, and there are plans for a remodeling rebate for home owners who install water efficient fixtures. However, any further conservation ordinances or incentives are on hold because they involve serious economic and political concerns in addition to the legal issues [Patrick Crimmins, TWC, personal communication, 1992]. Beyond that, any move by the City of

San Antonio prior to decisions in the Sierra Club vs USFWS lawsuit and pending Texas legislation is impossible.

Obviously the city is following the Sierra Club lawsuit carefully. The city does not want the Sierra Club to win or, more precisely, to have federal intervention in the region and, instead, would like to see a state-implemented management plan for all five districts controlled at a regional level. The only requests the City of San Antonio has made to the TWC is that the city's water rights be permanently guaranteed and that it receive no less than the historical maximum that it has used, which the TWC has agreed to [Patrick Crimmins, personal communication, 1992]. However, nothing concrete can be done by the city until the lawsuit is settled and the Texas Legislature makes a decision on the new legislative proposals. With a management plan in place, the City of San Antonio would most likely need some alternative water supplies to sustain future growth.

### 2.7.3 Farmers and Ranchers

The agricultural interests are represented mainly by the farmers of Uvalde and Medina Counties. For generations they have been able to draw as much water from the aquifer as they wanted based on existing Texas groundwater law, and that is the way they would like to keep it. This position has conflicted with other groups in the region that recognize the need to regulate consumption. As mentioned earlier, both of these counties pulled out of the EUWD largely due to the demands of the farmers in this area. Subject to any new legislation, they are well within their legal rights to continue current pumping practices and will likely do so.

### 2.7.4 Guadalupe-Blanco River Authority

The GBRA is in a legal situation similar to the farmers of Uvalde and Medina Counties. Their involvement with the issue is primarily as a lobby group with the intent to protect the interest of the people who rely on the Guadalupe and Blanco Rivers for their water. For generations they have drawn water from these rivers, and because these waters come from Edwards aquifer outflows, the GBRA's interests are closely dependent on the decisions made regarding the aquifer. Thus, the GBRA was also granted *amici curaie* status in the Sierra Club vs USFWS lawsuit.

Until decisions are made at the state or federal level, the regional and local governing bodies have very little control over the Edwards aquifer. They have made many attempts to conserve water through ordinances and have developed plans within the reach of their authority. The various groups have also made their positions on the issues fairly clear. However, they will have to remain in a holding pattern until legislation allows a viable management plan at any level.

## 2.8 SIERRA CLUB VS U.S. FISH AND WILDLIFE SERVICE

In 1991, former Arizona Governor Bruce Babbitt called the Sierra Club suit "a real hammer" of an incentive for state and regional interest groups to resolve the issue without federal intervention. He went on to say "Crisis is one, and unfortunately perhaps the most common, way to catalyze change." [Burkett, San Antonio Light, 1991]. While Babbitt was Governor, Arizona rewrote its state laws regarding the use of groundwater. Unfortunately, the hammer was not perceived as big enough to force the divergent interest groups to reach an agreement that would protect the habitat of the endangered species to the satisfaction of the Sierra Club. After numerous pre-trial motions and hearings, the case was heard in federal district court in Midland, Texas, in November 1992, and a ruling was issued in February 1993.

Depending on the State of Texas' response to the District Court ruling, the outcome of this case may be federally mandated groundwater pumping controls similar to those in effect at Devil's Hole, Nevada. At Devil's Hole, groundwater withdrawals are controlled by federal court decree to protect the desert pupfish, an endangered species that lives in several small underground lakes near Death Valley [Babbitt, 1991]. Many groups of people will be impacted no matter what results from this lawsuit. If pumping restrictions are instituted, the economy and residents of San Antonio will surely be affected as will the surrounding farming communities. Without limitations on pumping, the "downstream users" who rely on surface waters augmented by springflow from the San Marcos and Comal Springs will find the water available to them diminished in dry years, and several endangered species may perish.

### 2.8.1 The Parties

The "battle lines" in this legal dispute over management of the Edwards aquifer are clearly seen in the list of parties who requested or received intervenor status from the federal court. Listed below are the parties who aligned themselves with either the Plaintiff (Sierra Club), those in favor of pumping limitations or aquifer management, or the Defendant (USFWS), those opposed to any federally imposed restrictions on groundwater pumping. Many others requested *Amici Curiae* status (friend of the court), which allowed them to submit evidence and cross examine witnesses introduced by either party [Sierra Club vs USFWS, 1992]:

| | |
|---|---|
| Plaintiff Intervenors: | GBRA, City of San Marcos, City of New Braunfels and New Braunfels Utilities, Bexar Metropolitan Water District, Green Valley Water Supply Corporation, and Atascosa Rural Water Supply Corporation. |
| Defendant Intervenors: | State of Texas, City of San Antonio, a group of "Industrial Water Users," Greater San Antonio Builders Assoc., three individual farmers (Danny McFadin, Tommy Walker, Carl Muecke), and the Living Waters Artesian Springs, Ltd. (the catfish farm). The TWC and the Dept. of Parks and Wildlife requested Plaintiff Intervenor status but were aligned with the defendant by the federal judge, along with the Texas Department of Agriculture. |
| *Amici Curiae*: | EUWD, a group of "Industrial Water Users" from the Lower Guadalupe River Association, and Thelma Area Neighborhood Corp. |

This listing of interested parties shows the intense nature of the problem. A motion filed by the federal agencies involved requested the federal judge to control the litigation. The motion warned "This case should not be transformed into the lawyers' relief fund for Central Texas, particularly at the expense of taxpayers who would be required to pay for any award of attorneys' fees awarded under the Endangered Species Act" [Elliot, 1991].

### 2.8.2 The Act

The Endangered Species Act became federal law in 1973 in an effort by Congress to stop unrestrained development which was increasing the number of species becoming extinct. The law forbids acts by public or private entities having an adverse impact on federally listed ("endangered or threatened") species or their habitat. Any activity causing such an impact is called a "taking." A taking would occur at the point springflows were less than that required to maintain the habitat of the listed species [Pressley, 1991; Sierra Club vs USFWS, 1993]. "Jeopardy" of a listed species occurs when the species or its habitat is affected to the extent that the species cannot fully recover in its natural environment; that is, the actions drive a species to or near extinction.

Under the Act, federal agencies have an "affirmative" action to develop programs to conserve listed species and not just avoid actions which harm endangered species [Pressley, 1991]. This requirement is at the heart of the Sierra Club lawsuit, which contends that the USFWS has failed to develop and implement programs that would be effective in allowing the species to recover from their endangered or threatened status. Also, the Sierra Club suit contends that due to the lack of positive measures to avoid harm to the species, they have been jeopardized by periods of low springflow.

### 2.8.3 The Suit

The Sierra Club suit claimed that [Sierra Club vs USFWS, 1992]:

> There are listed species that exist only at Comal Springs, San Marcos Springs, and within the Edwards aquifer.
>
> The USFWS has a duty to develop and implement a plan to conserve and ensure the survival of listed species.
>
> The USFWS developed but never implemented a San Marcos Recovery Plan for the listed species within the San Marcos Springs. This plan states that the most serious threat to the listed species is reduced springflows caused by overdrafting of the Edwards aquifer.
>
> Although the same threat applies to listed species at Comal Springs and those in the Edwards aquifer, no conservation and recovery plans have been developed to protect species living there.
>
> Failure to develop and implement conservation and recovery plans has resulted in (1) the possible extinction of the San Marcos Gambusia, (2) recent takings of fountain darters at Comal Springs, and (3) the destruction of Texas wildrice and a portion of its critical habitat.

The USFWS claimed that:

> Although withdrawals from the Edwards aquifer are the greatest threat to these listed species, the USFWS did not study the relationship of these withdrawals to the cessation of flow at Comal Springs in 1956 or to low flows in 1984, 1989, and 1990.
>
> The San Marcos Recovery Plan will be modified to cover Comal Springs as well.
>
> The USFWS has discretion under the Endangered Species Act and must comply with certain funding constraints. State and local authorities are better equipped to regulate groundwater withdrawals. Thus, the USFWS has relied on state and local authorities to develop and implement conservation and recovery plans.

The issues of law contested were:

> Does the USFWS have discretionary authority to decide if and when to develop and implement conservation and recovery plans for endangered species? Can the failure to do so be excused by lack of resources?

The issues of fact contested were:

> Did the USFWS fail to develop and implement recovery plans to provide minimum springflows, thereby failing to promote the survival and recovery of the listed species in their natural environment?

Facts and issues not in dispute which had been established through a series of proceedings or submissions to the court from either party were:

> Springflow of less than 100 cfs will cause harm to and taking of the fountain darter at Comal Springs. The entire population of fountain darters is jeopardized if springflow ceases.

Comal Springs ceased flowing in 1956, causing the possible extermination of the fountain darters living there. Groundwater withdrawals led to reduced flows in 1984, 1989, and 1990, and if continued unchecked will eventually cause Comal and San Marcos Springs to dry up.

The San Marcos Recovery Team conceded that springflow augmentation is not a viable alternative.

The USFWS took no significant steps to implement the San Marcos Recovery Plan since it was approved in 1985.

State and local measures have failed to provide protection for minimum springflows necessary for critical habitat. Unless an Endangered Species Act incidental take permit is issued by USFWS, the flow at Comal Springs must equal at least 100 cfs. No incidental take permit could be issued which would allow flow to cease at Comal Springs.

### 2.8.4 Pertinent Case Law

The U.S. Supreme Court recently decided a case which restricts the ability of groups like the Sierra Club to bring citizens lawsuits against the federal government [Sierra Club, undated]. Previously, organizations like the Sierra Club had been able to pursue citizens' suits as an avenue to ensure that administrative governmental agencies stay within the authority granted them by legislative bodies. Bringing citizens' suits against the federal government now requires that someone within the group have a specific interest in the action. The Sierra Club contended that members of the organization take frequent field trips to the springs to enjoy the ecosystems and species and therefore have an interest in the action [Sierra Club vs USFWS, 1993].

A case decided in 1977 provides that the USFWS has an affirmative duty to protect and conserve endangered species, not just prevent harm to them from actions of the government or private individuals. This duty to conserve requires the USFWS to develop and implement plans to protect listed species until they no longer require protection. Other cases have held that priority must be given to the endangered species over all other purposes of a particular project [Pressley, 1991]. Several other cases provide precedence that harming critical habitat constitutes taking of a listed species [Pressley, 1991]. These cases show that the federal court has the power to impose pumping restrictions on the Edwards aquifer as was done in the Devil's Hole, Nevada case.

### 2.8.5 The Ruling

On January 30, 1993, District Judge Lucius Bunton ruled in favor of the plaintiff and plaintiff-intervenors. Among the judge's orders were the following [Sierra Club vs USFWS, 1993]:

The USFWS shall determine within 45 days critical springflows at Comal and San Marcos Springs. Until then, springflows as found by the court will constitute interim springflow findings (in the range of 100 cfs).

The USFWS must advise all participating federal agencies of each minimum springflow and the Edwards aquifer level so that those agencies can perform their duties under the Endangered Species Act if the State of Texas fails or refuses to regulate withdrawals from the Edwards aquifer to the extent required to protect the listed species.

The USFWS must advise all those withdrawing water from the Edwards aquifer of each minimum springflow and aquifer level so that pumpers will be able to take appropriate action if the State of Texas fails or refuses to regulate withdrawals.

By March 1, 1993, the TWC must prepare a plan to insure that Comal and San Marcos Springs do not drop below levels which place the listed species in jeopardy.

If by May 31, 1993, the State of Texas does not have in effect a regulatory system which protects the listed species, even during a repeat of the drought of record, the plaintiff and plaintiff-intervenors may seek appropriate relief.

Thus, it was ruled that the USFWS did not develop sufficient conservation and recovery plans, and that they were not excused from doing so by a lack of resources. The implication for the State of Texas is that, if the State Legislature and the TWC do not act quickly to manage the Edwards aquifer, federal mandates—such as those instituted in Devil's Hole—may be imposed on users of the Edwards aquifer.

## 2.9 PROPOSED LEGISLATION

In light of this federal ruling, and the failure of local and regional interest groups to agree on a management plan, it is perhaps fortuitous for the State of Texas that two state legislators introduced bills in the 1993 legislative session. One bill was based on a modification of the 1992 TWC management plan; the other favored agriculture water rights.

The TWC plan is based on the designation of the Edwards aquifer as an underground river. As such, the water flowing within the Edwards aquifer is state water. The Edwards aquifer has always been considered an aquifer subject to private ownership. This new designation as state water would mean no one could divert Edwards aquifer water without prior approval by the state. Previous unauthorized diversions of state water would not be considered a basis for a vested interest in the water. This raises the question of whether state regulation of the Edwards aquifer constitutes a "taking" of private property. If considered a taking, individuals would have to be compensated for limitations placed on their property rights.

## 2.10 CONCLUSION

The only means of protecting this tremendous resource, the Edwards aquifer, is to implement a management plan. The Texas Water Commission has sought to implement a plan with its Management Plan for the Edwards Aquifer [TWC, 1992] and the subsequent "Rules." Unfortunately all parties were not in agreement, and mediation resulted in little or no compromise. Thus, the plan cannot be implemented without some legal action. Legal action consisting of the courts upholding the Edwards aquifer as an underground river or the courts upholding the constitutionality of Texas Water Code §28.011 is sure to be costly and a very time consuming process. Furthermore, more litigation is likely to result from the courts making decisions on either of these issues. To prevent federally mandated pumping restrictions, the Legislature of the State of Texas must work to provide clear authority to the TWC, the EUWD, or some other superdistrict to manage the Edwards aquifer. Until all parties can agree or the Legislature acts, the State is at risk of losing many benefits from this extraordinary resource.

# 3.0 ECONOMICS AND DEVELOPMENT

Richard L. Bowers, Kerry E. Keiser, Tri M. Truong,
Daene C. McKinney, and David W. Watkins, Jr.

## 3.1 USE OF THE EDWARDS AQUIFER—PAST, PRESENT, FUTURE

To evaluate the use of water from the Edwards aquifer, water use in five counties overlying the aquifer is considered. These are Bexar, Comal, Hays, Medina, and Uvalde Counties. Data obtained from the TWDB includes the historical use of water, population projections, and water demand projections through the year 2030 for each of these counties [TWDB, 1992a]. These data are divided into surface water and groundwater categories and by sectors of water use—municipal, industrial, irrigation, and livestock.

To estimate the portion of overall water use from the Edwards aquifer, the historical groundwater use from 1980 to 1990 was adjusted with appropriate factors. Using historical pumpage data [TWDB, 1992b], the historical groundwater use for each county was multiplied by that county's fraction of pumpage from the Edwards aquifer. The total historical use of the aquifer is estimated to be the sum of these values for all five counties. The projected demand on the aquifer by each county can then be estimated by multiplying the projected total water demand by the "groundwater fraction" of total historical use times the fraction of groundwater taken from the Edwards aquifer. The total use of water for the five counties is summarized in Table 3.1 and Figure 3.1. It is quite clear that the region is heavily dependent upon the Edwards aquifer for most of its water, particularly for municipal supply.

The five counties under consideration are expected to grow considerably in population over the next 40 years, which would expectedly increase the municipal water demand by a substantial amount. The TWDB has produced high and low series population projections for the region which account for variables such as fertility, mortality, and migration rates. These projected values (Table 3.2 and Figure 3.2) are commensurate with other projections [Institute for Population Research, 1988].

The ensuing water demand on the Edwards aquifer for 1990-2030 can be computed based on the assumption that no changes are made in the water usage scheme by each sector, and that no new water resources are incorporated. The projected demands are shown in Table 3.3 and Figures 3.3 and 3.4, where each value is the sum over the five counties of the projections described above. When compared to the average annual

**Table 3.1** Average Water Use 1980-1990 for Bexar, Comal, Hays, Medina, and Uvalde Counties [TWDB, 1992a]

| | SW AF/yr | GW AF/yr | EA GW AF/yr | % GW | % pumpage from EA | % total use from EA |
|---|---|---|---|---|---|---|
| Municipal | 734 | 257,059 | 256,288 | 99.7 | 97.8 | 97.5 |
| Industry | 28,006 | 21,014 | 9,015 | 42.9 | 66.7 | 28.6 |
| Irrigation | 66,985 | 210,312 | 159,416 | 75.8 | 99.3 | 75.3 |
| Livestock | 3,392 | 1,617 | 522 | 32.3 | 71.3 | 23.0 |
| Agriculture | 70,377 | 211,929 | 159,939 | | | |
| TOTAL | 99,117 | 490,002 | 407,682 | 83.2 | 97.0 | 80.7 |

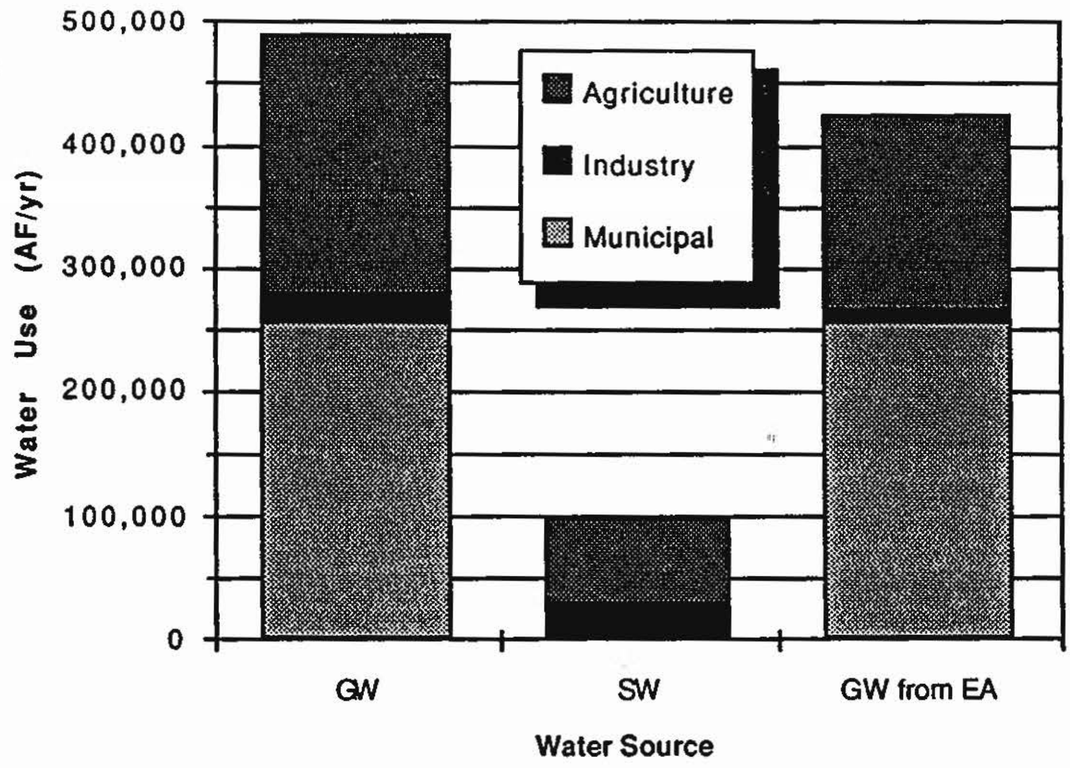



**Figure 3.1** Average Water Use 1980-1990 for Bexar, Comal, Hays, Medina, and Uvalde Counties [TWDB, 1992a]

Table 3.2 Projected Population of Bexar, Comal, Hays, Medina, and Uvalde Counties (TWDB, 1992a)

| | 1990 | 2000 | 2010 | 2020 | 2030 |
|---|---|---|---|---|---|
| Low Series Projection | 1,353,492 | 1,591,009 | 1,858,057 | 2,145,636 | 2,476,492 |
| High Series Projection | 1,353,492 | 1,646,034 | 1,994,833 | 2,383,772 | 2,854,403 |

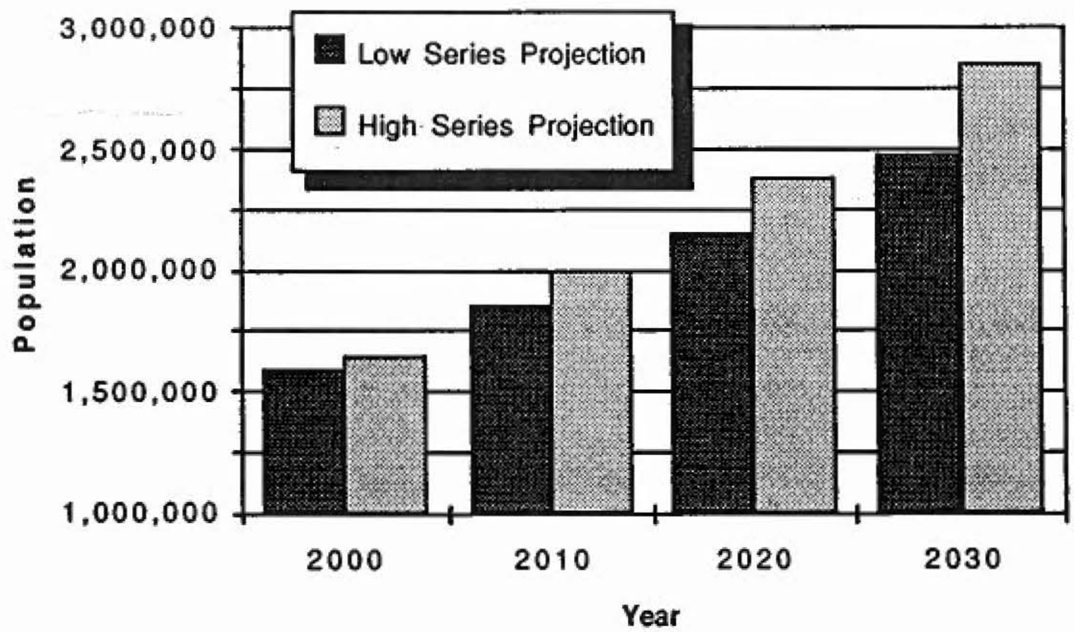



Figure 3.2 Projected Population for Bexar, Comal, Hays, Medina, and Uvalde Counties

Table 3.3a Total Water Demand for Bexar, Comal, Hays, Medina, and Uvalde Counties (AF/yr)

| | | Low Series Projections | | | | High Series Projections | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1990 | 2000 | 2010 | 2020 | 2030 | 2000 | 2010 | 2020 | 2030 |
| Municipal[1] | 257,713 | 332,219 | 386,226 | 441,603 | 512,031 | 343,267 | 413,724 | 492,561 | 588,493 |
| Municipal[2] | — | 385,220 | 448,172 | 516,242 | 128,970 | 397,987 | 479,936 | 571,763 | 683,594 |
| Municipal[3] | — | 320,198 | 356,736 | 393,665 | 445,306 | 330,708 | 380,096 | 435,408 | 511,394 |
| Municipal[4] | — | 371,048 | 413,773 | 458,429 | 520,601 | 383,305 | 442,708 | 505,655 | 597,820 |
| Industry | 45,752 | 71,057 | 75,337 | 79,705 | 82,851 | 73,565 | 84,979 | 97,520 | 115,593 |
| Irrigation | 335,860 | 198,950 | 119,535 | 116,545 | 114,521 | 241,160 | 246,400 | 245,040 | 243,680 |
| Livestock | 4,922 | 6,360 | 6,360 | 6,360 | 6,360 | 6,360 | 6,360 | 6,360 | 6,360 |
| Agriculture | 340,782 | 205,310 | 125,895 | 122,905 | 120,881 | 247,520 | 252,760 | 251,400 | 250,040 |
| Total[1] | 644,247 | 608,586 | 587,458 | 644,213 | 715,763 | 664,352 | 751,463 | 841,481 | 954,126 |
| Total[2] | — | 661,587 | 649,404 | 718,852 | 332,702 | 719,072 | 817,675 | 920,683 | 1049227 |
| Total[3] | — | 596,565 | 557,968 | 596,275 | 649,038 | 651,793 | 717,835 | 784,328 | 877,027 |
| Total[4] | — | 647,415 | 615,005 | 661,039 | 724,333 | 704,390 | 780,447 | 854,575 | 963,453 |

[1] Municipal assumes average per capita water use.
[2] Municipal assumes high per capita water use.
[3] Municipal assumes average per capita water use with conservation practices.
[4] Municipal assumes high per capita water use with conservation practices.

Table 3.3b Water Demand on Edwards Aquifer (AF/yr)
[= Total Demand * % Use From Edwards Aquifer]

| | | Low Series Projections | | | | High Series Projections | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1990 | 2000 | 2010 | 2020 | 2030 | 2000 | 2010 | 2020 | 2030 |
| Municipal[1] | 251,270 | 323,914 | 376,570 | 430,563 | 499,230 | 334,685 | 403,381 | 480,247 | 573,781 |
| Municipal[2] | — | 375,590 | 436,968 | 503,336 | 125,746 | 388,037 | 467,938 | 557,469 | 666,504 |
| Municipal[3] | — | 312,193 | 347,818 | 383,823 | 434,173 | 322,440 | 370,594 | 424,523 | 498,609 |
| Municipal[4] | — | 361,772 | 403,429 | 446,968 | 507,586 | 373,722 | 431,640 | 493,014 | 582,875 |
| Industry | 13,085 | 20,322 | 21,546 | 22,796 | 23690 | 21,040 | 24,304 | 27,891 | 33,060 |
| Irrigation | 252,903 | 149,809 | 90,010 | 87,758 | 86,249 | 181,593 | 185,539 | 184,515 | 183,491 |
| Livestock | 1,132 | 1,463 | 1,463 | 1,463 | 1,464 | 1,463 | 1,463 | 1,463 | 1,463 |
| Agriculture | 254,035 | 151,272 | 91,473 | 89,221 | 87,713 | 183,056 | 187,002 | 185,978 | 184,954 |
| Total[1] | 518,390 | 495,508 | 489,589 | 542,580 | 610,633 | 538,781 | 614,687 | 694,116 | 791,794 |
| Total[2] | — | 547,184 | 549,987 | 615,353 | 237,149 | 592,133 | 679,244 | 771,338 | 884,518 |
| Total[3] | — | 483,788 | 460,837 | 495,840 | 545,576 | 526,536 | 581,900 | 638,391 | 716,623 |
| Total[4] | — | 533,366 | 516,448 | 558,985 | 618,989 | 577,818 | 642,946 | 706,882 | 800,888 |

[1] Municipal assumes average per capita water use.
[2] Municipal assumes high per capita water use.
[3] Municipal assumes average per capita water use with conservation practices.
[4] Municipal assumes high per capita water use with conservation practices.

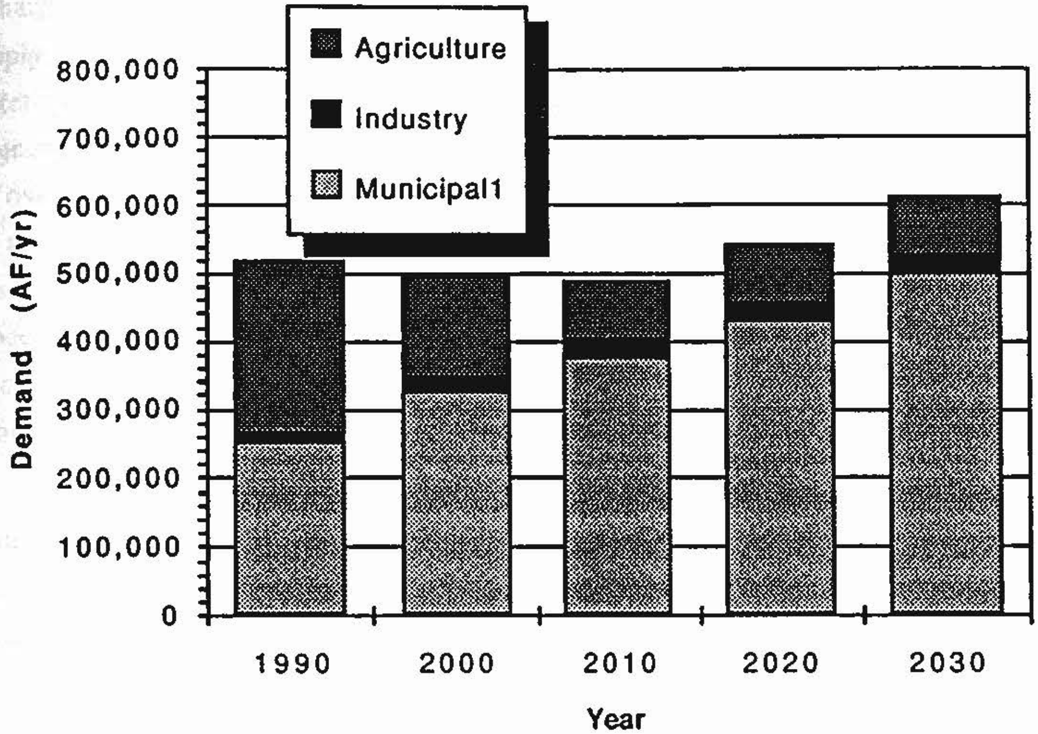



**Figure 3.3** Water Demand on Edwards Aquifer (Low Series)

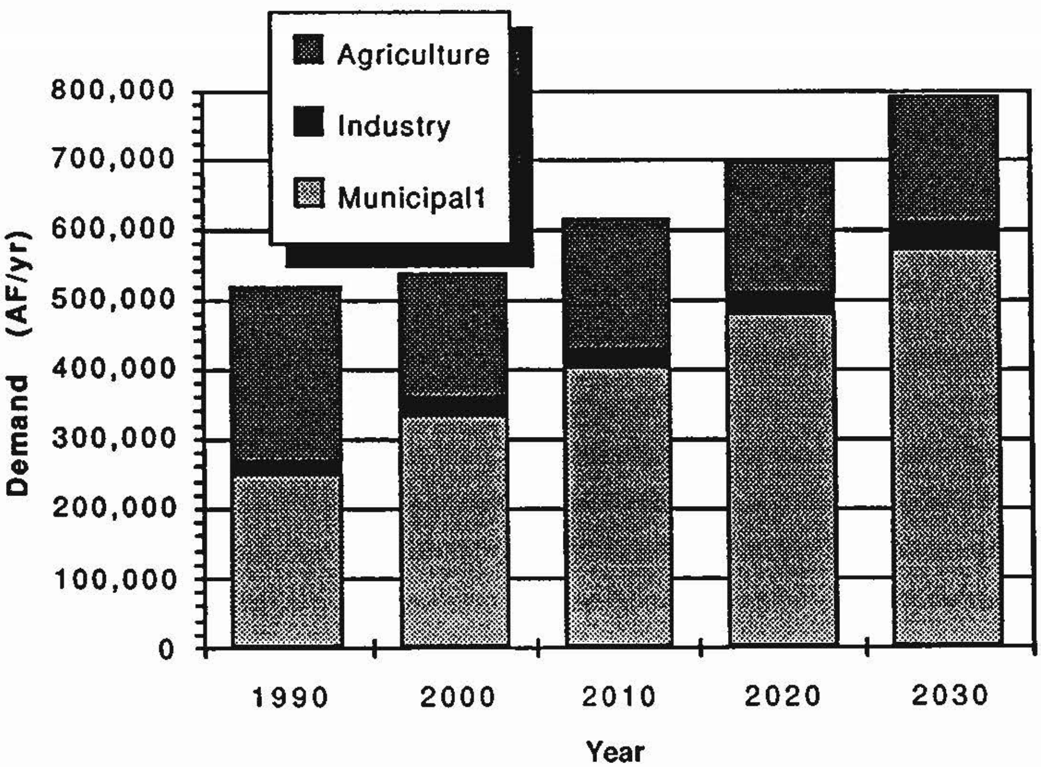



**Figure 3.4** Water Demand on Edwards Aquifer (High Series)

recharge of the aquifer (604,500 AF/yr), this illustrates the magnitude of the future water supply deficit that the region faces if new resources are not explored and the usage pattern does not change. As expected, both the low and high series water demand projections show that increases in municipal demand have the most significant impact on the overall demand increases. The projections show a decrease in irrigation demand from the aquifer, probably from reduced acreage and more efficient use of irrigation water. It is seen that even with municipal conservation practices, municipal demand is still expected to increase significantly. Industrial use of water from the aquifer does not show much increase, possibly because of the applicability of surface water for that use (57.1% of historical industrial water use is from surface water).

The TWC management plan specifies that by 2008, total pumpage shall be reduced to 400,000 AF per year or less. Based on the current 538,000 AF per year estimated usage [TWC, 1992], this region clearly faces an increasing demand on, and a decreasing supply of, water from the Edwards aquifer. Although the plan addresses water use curtailment by the various users of the aquifer when levels are low, this appears to be a temporary measure meant to protect springflows and does not affect the imminent shortage of water for municipal purposes. Even when aquifer levels are high, if pumpage of the Edwards aquifer is to be held below 400,000 AF per year, other water resources must be made available to meet the future demand. Based on the above projections, by 2010 an estimated 70,000 to 200,000 AF per year of water from other sources will be necessary to satisfy demand. By 2030 this figure will reach 200,000 to 400,000 AF per year. If water demands are to be met without the development of alternative sources of water, the goal of limiting pumpage of the aquifer is far out of reach.

## 3.2 ECONOMIC IMPACT OF WATER RESTRICTIONS

Studies have been made on the comparative value of water for such uses as irrigation, industry, municipal, recreation, hydroelectric power generation, fish and wildlife habitat, and navigation [Speidel, 1988; Gibbons, 1986]. However, no studies have been made to put a value on water in the Edwards aquifer region. Thus, this assessment of the economic impact of water restrictions on the different economic sectors will mainly focus on the comparative employment and production of these sectors and their respective water use. Performing such a comparison will show the relative importance of each sector to the region's economy and thereby provide the basis for recommendations on how to restrict water to the different sectors most economically.

The 1980 employment data are summarized in Table 3.4 and Figure 3.5. Current and projected water use by sector for the study area is shown in Figures 3.3 and 3.4. Note that although agriculture employs less than 2 percent of the total, it consumes approximately 50 percent of the water in the Edwards aquifer region in 1990. Note also that, in the low-series projections, industrial water use is projected to stay basically constant until 2030.

### 3.2.1 Agriculture

The value of water in agriculture can be "measured in terms of the increment of profit to the producer with irrigation as compared with profits without irrigation" [Speidel, 1988]. The TWC management plan calls for a "dry-year" option contract in which the TWC would pay farmers for not irrigating fields during dry years. Since the government pays the farmer for any loss in profits, there is no change in the economic value of water in agriculture during dry years and thus no economic impact on farmers if the "dry-year" option contract is implemented. If it is not implemented, and farmers' water efficiency remains constant, a 12% decrease in farmers' profits will be incurred due to increased costs of pumping from lower water levels [CH2M Hill, 1986].

### 3.2.2 Business and Industrial

Figure 3.5 shows that much of the economy in the study area is non-manufacturing. These industries have relatively low water use intensity so they would not be significantly impacted by water restrictions. The manufacturing industry (especially the food, textile,

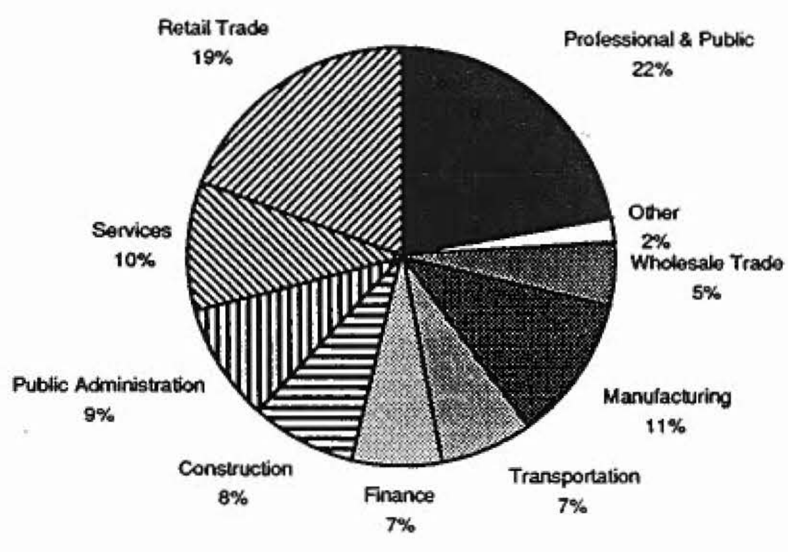



**Figure 3.5** Employment Characteristics for Bexar, Comal, Hays, Medina and Uvalde Counties [USDOC, 1983]

**Table 3.4** Employment Characteristics for Bexar, Comal, Hays, Medina and Uvalde Counties (U.S. Department of Commerce, 1983)

| Employment Sector | Study Area | Bexar Co. | Comal Co. | Hays Co. | Medina Co. | Uvalde Co. |
|---|---|---|---|---|---|---|
| Agriculture | 6,106 (1%) | 3,411 (1%) | 347 (2%) | 454 (3%) | 874 (10%) | 1,020 (12%) |
| Forest & Fisheries | 83 (<1%) | 44 (<1%) | 7 (<1%) | 14 (<1%) | 6 (<1%) | 12 (<1%) |
| Mining | 3,339 (1%) | 2,332 (1%) | 154 (1%) | 103 (1%) | 284 (3%) | 466 (6%) |
| Construction | 34,823 (8%) | 29,596 (8%) | 1,927 (12%) | 1,589 (10%) | 1,022 (12%) | 689 (8%) |
| Manufacturing (Nondurable Goods) | 24,189 (5%) | 21,563 (6%) | 1,550 (10%) | 376 (2%) | 250 (3%) | 450 (5%) |
| Manufacturing (Durable Goods) | 25,840 (6%) | 22,292 (6%) | 1,375 (9%) | 1,502 (9%) | 515 (6%) | 156 (2%) |
| Transportation, Comm., Utilities | 28,766 (7%) | 25,944 (7%) | 1,059 (7%) | 602 (4%) | 586 (7%) | 575 (7%) |
| Wholesale Trade | 22,469 (5%) | 20,363 (5%) | 615 (4%) | 479 (3%) | 438 (5%) | 574 (7%) |
| Retail Trade | 80,516 (19%) | 72,149 (19%) | 2,706 (17%) | 3,022 (18%) | 1,376 (16%) | 1,263 (15%) |
| Finance, Insurance, Banking, Real Estate | 28,287 (7%) | 26,849 (7%) | 888 (6%) | 863 (5%) | 402 (5%) | 285 (3%) |
| Services (Business and Personal) | 42,267 (10%) | 38,032 (10%) | 1,315 (8%) | 1,508 (9%) | 630 (7%) | 782 (9%) |
| Services (Professional and Public) | 93,554 (22%) | 82,256 (22%) | 2,854 (18%) | 5,321 (31%) | 1,483 (17%) | 1,640 (20%) |
| Public Administration | 39,803 (9%) | 36,868 (10%) | 848 (5%) | 1,076 (6%) | 657 (8%) | 354 (4%) |
| TOTAL | 431,045 | 381,699 | 15,645 | 16,909 | 8,526 | 8,266 |

glass, stone, and clay product industries which account for around 90% of the manufacturing water use) would be greatly impacted by any restrictions in water use since it is a vital resource in most manufacturing processes. However, manufacturing industries use only 4% of total water use in the area, whereas they account for around 27% of the area's total value of output, income, and employment [CH2M Hill, 1986].

#### 3.2.3 Recreation and Tourism

If water restrictions were imposed, the major impact on recreation and tourism would be on Comal and San Marcos Springs. These springs account for approximately 5 to 6% of the economic output and 5% of the employment in Comal and Hays Counties. However, this is less than 1% of the output in the whole Edwards aquifer region [CH2M Hill, 1986]. If no new policies are instated, up to 90% of the economic activity related to the Comal and San Marcos Springs could be lost. Recreational activities such as canoeing, rafting, and tubing will cease if the springs go dry.

### 3.3 ALTERNATIVE WATER SOURCES

With the projected increase in water withdrawals from the Edwards aquifer, especially in the San Antonio region, new water sources should be investigated as a way to avoid water restriction measures. Various alternative water sources have been suggested for the Edwards aquifer region to supplement existing sources. Some of these have been deemed infeasible due mostly to economic or legal reasons. Others that have been deemed feasible have not been implemented because of a lack of public and political support. Though the feasible alternatives could have a beneficial impact on existing water supplies, they are not without drawbacks, which are usually environmental. The following is a listing and explanation of alternative water sources as they relate to the Edwards aquifer. Where possible, the cost to implement the different alternatives and the estimated percentage increase in existing water supplies are given.

#### 3.3.1 Viable Alternatives

The alternatives deemed to be viable are presented here with economic and environmental impacts taken to be of foremost importance. Legal considerations were accounted for where possible, but political considerations were not considered.

Reclaimed Water

Reclaimed water can come from either irrigation return flows or from municipal effluents. Though there is a great potential for reuse of irrigation runoff, it is not feasible because the runoff is spread over such a wide area of the Guadalupe, San Antonio, and

Nueces River Basins [CH2M Hill, 1986]. Municipal effluent reuse, on the other hand, could prove to be a viable alternative, with the possibility of a 25% or more reduction in water demand resulting from its implementation [CH2M Hill, 1986]. In 1989, the Alamo Conservation and Reuse District (ACRUD) was created by San Antonio. It is expected that by the year 2010, an extra 90,000 acre-feet of water will be available due to this project as stated in the ACRUD Master Plan of August 1990.

San Antonio is the only major city in the study area which would be able to sustain a reclaimed water program because its effluent constitutes about 70% of the overall municipal and industrial (M&I) return flow for the Guadalupe, San Antonio, and Nueces River Basins. By the year 2000, the municipal effluent flow from San Antonio is estimated to be 167,000 AF per year, and by 2010 this is estimated to increase to 196,000 AF per year [Special Committee, 1991]. Because San Antonio already has three wastewater treatment plants (Leon Creek, Salado Creek, and Dos Rios), which have a combined capacity of 172,000 AF per year, major investments in new facilities would not be needed.

Agricultural irrigation is one of the common applications of wastewater reuse. However, there are health concerns associated with effluent reuse, especially for sprinkler irrigation systems which have the potential of transporting pathogens to nearby areas. Using the land itself as an advanced water treatment process has also been investigated. The three most common methods are slow-rate irrigation, overland flow, and rapid infiltration-percolation [CH2M Hill, 1986]. The idea in the first two methods is for the plants to use the nutrients in the water. The difference between them is that with slow-rate irrigation the water percolates into the soil or is absorbed by the plants, whereas for overland flow it does not. In rapid infiltration-percolation, the wastewater is delivered to highly permeable soils. As it percolates through the soil it is treated by natural processes, and eventually it recharges the ground water sources. Though studies have been performed which showed that yields of crops irrigated with wastewater are not adversely affected, yields vary with different crops and the primary and secondary waste water treatment used [Speidel et al., 1988]. Municipal effluent would have to be transported from San Antonio to the Bexar-Medina-Atascosa Water Improvement District No. 1 or to the Western Bexar or Eastern Medina Counties for it to be used effectively for irrigation. The cost of the transport system would be about $190 to $270 per acre-foot.

Municipalities and industry may also use reclaimed water. Specific candidates for waste water reuse are cooling towers for electric steam power plants, landscape irrigation (especially parks and golf courses), residential irrigation, and military facilities. Power plants already use waste water effluents in their cooling towers, but use could be expanded to around 60,000 AF/yr. Reuse of wastewater for landscape irrigation could amount to 7,000 AF/yr of savings. Reuse of wastewater for residential irrigation would be most feasible for new developments which have the potential of separating the potable water distribution system from the lawn or outdoor distribution system. Southwest Texas State University has started a pilot project for such a system which is estimated to save the campus about 500,000 gallons per day if implemented campus wide.

Note that reuse of wastewater means that the San Antonio River, which would normally be the recipient of the wastewater, would then be short by the amount of wastewater reuse. This could have both environmental consequences as well as legal consequences if the state, or another institution, were to determine that San Antonio were required to maintain a certain level of discharge (which it presently does not). Suggestions of maintaining a discharge level of at least 105,000 AF/yr have been made [CH2M Hill, 1986].

Weather Modification

Because of the proximity of the Gulf of Mexico to the San Antonio region, cloud seeding has been seen as a viable alternative. A four-year cloud seeding program was conducted by the EUWD from 1985 to 1989. Unfortunately, the data from this program were not located so the final results are not presented here. Cloud seeding would only be a viable alternative during wet years, however, since water needs during a drought probably could not be met on a consistent basis with this method.

Vegetation Management

The idea behind vegetation management is that reduction or conversion of vegetation in undeveloped areas could decrease the amount of water lost to such vegetation. In the Hill Country, mesquite and cedar seem to have the greatest potential for management. Runoff in this area can be increased by as much as 2.5 inches per acre per year if vegetative management is practiced [Special Committee, 1991]. More studies are needed in this area to get a clearer understanding of what is required in vegetation management, how much water can be saved, and what other environmental impacts must be considered.

Artificial Recharge

Numerous recharge reservoirs and dams have been built and proposed for the Edwards aquifer region. A partial listing of existing and proposed projects is presented in Table 3.5. Basically, artificial recharge is accomplished by the use of dams or reservoirs

**Table 3.5** Edwards Aquifer Recharge Projects, Existing and Proposed

| Facility | Capacity (AF/yr) | Ave. Annual Recharge (AF/yr) | Capital Cost ($10^3$ $) | Projected Cost per Acre-ft. ($) | Source |
|---|---|---|---|---|---|
| **Existing** | | | | | |
| Parker Creek | 2,661 | 401 | | | [HDR, 1991] |
| Middle Verde Creek | 150 | 853 | | | " |
| San Geronimo Creek | 271 | 462 | | | " |
| Seco Creek | 2 | 2,183 | | | " |
| **Proposed** | | | | | |
| Centex Reservoir | 271 | 768 | 602 | 92.72 | [Rauschuber, 1992] |
| Ruby Reservoir | 435 | 1,152 | 952 | 89.52 | " |
| Rutherford Dam & Res. | 3,670 | 3,515 | 2,856 | 89.52 | " |
| Centex Quarry | 1,000 | 5,718 | 1,318 | 31.97 | " |
| Nueces-West Nueces | 252,300 | 41,309 | | | [Special Committee, 1991] |
| Frio-Dry Frio: | | 16,306 | | | " |
| (1) Upper Dry Frio | 60,000 | | | | " |
| (2) Concan | 149,000 | | | | " |
| Sabinal | 93,300 | 12,226 | | | " |
| Between Sabinal & Medina: | | 15,420 | | | " |
| (1) Upper Seco | 23,000 | | | | " |
| (2) Upper Hondo | 47,000 | | | | " |
| (3) Upper Verde | 23,000 | | | | " |

on "recharging streams to capture and store stormwater runoff, which then can be infiltrated into the groundwater system either as seepage directly from the impoundments or, once released, as channel losses through the fractures and openings along the streambeds below the dams" [CH2M Hill, 1986]. The potential benefits of enhanced recharge of the aquifer include increased springflows; increased water levels in the unconfined parts of the aquifer, resulting in decreased pumping requirements and increased storage during dry years; and the relatively small size of the diversion structures needed, resulting in lower costs and less risk of environmental destruction. The area with the most potential for recharge seems to be the Nueces River Basin. With regard to increasing springflows, San Marcos Springs would benefit the most from projects in the Blanco River Basin, while Comal Springs would not benefit much from artificial recharge because it is not situated near sources of recharge [Rauschuber & Assoc., 1992].

There are some drawbacks to the recharge structures which must be considered. First, artificial recharge could decrease the surface water available for downstream flow. This is an important consideration mainly for the Nueces River since the recharge water would go into spring flows, which feed the Guadalupe and Blanco Rivers. Second, the dams or reservoirs would cause inundation of the areas around them, possibly damaging the surrounding environment. Smaller channel dams and reservoirs constructed on the streams which traverse the recharge zone have been suggested as a way of alleviating some of the environmental worries. The final drawback to these projects is the cost of buying the land where these dams or reservoirs would be located.

Reservoirs

Historically, new reservoirs have been seen as the major way of planning for dry-year water shortages. Up to five new reservoirs have been suggested for construction by 2010 [CH2M Hill, 1986]: Applewhite (50,000 AF/yr yield), Cibolo (25,000 AF/yr yield), Curero I and II (302,000 AF/yr yield), and Goliad (132,000 AF/yr yield). The major drawbacks of any of these projects have been the cost and the environmental impact of such reservoirs. The benefits are, of course, the definite increase in the supply of available water as well as side benefits such as recreation. Applewhite, the only reservoir which has been started to date, is in a state of limbo.

### 3.3.2 Infeasible Alternatives

Studies into alternative water sources have concluded that some are infeasible because of economic, environmental, or legal considerations. These alternatives are listed here as references for any future studies.

Importation of Surface Water

The 1990 Texas Water Plan [TWDB, 1990] summarized water supplies and demands for major river and coastal basins in Texas. From this data, it is possible to determine which river systems would be able to supply water to the Edwards aquifer region. The San Antonio region has no surplus surface water that could be used to supplement the Edwards aquifer [CH2M Hill, 1986]. River basins in the northeastern part of the state, including the Sulphur, Sabine, Neches, Trinity, San Jacinto Rivers, and the Cypress Creek Basin, would be possible sources of additional surface water. However, the excessive cost of a conveyance system which would cover such distances would be prohibitive. Note that there are also statutory limitations which, for planning purposes, give priority of water use to intrabasin demands for the next 50 years [Texas Water Code §16.052].

Desalinated Water Use

Major saline aquifers in the region include the Edwards/Glen Rose aquifer south of the badwater line and the Carrizo-Wilcox aquifer. Salinities in the Edwards/Glen Rose aquifer range from 1,000 to more than 150,000 mg/L of total dissolved solids and in the Carrizo-Wilcox aquifer from 3,000 to 60,000 mg/L [Rauschuber, 1990]. If desalination of saline groundwaters were used, reverse osmosis would be the most likely treatment process. Because of the high cost of treatment and the problems associated with the disposal of salt brine effluents, desalination was deemed to be infeasible.

## 3.4 CONSERVATION METHODS

Whether through the TWC plan for the Edwards aquifer, a market-based system for water rights, or another plan, water conservation must be an integral part of any water management plan. This section examines different types of water conservation methods, compares their costs and benefits, and offers some implementation mechanisms.

Section 298.15 of the TWC plan [TWC, 1992] requires a conservation plan to be submitted with any application for water permits. The amount of water must be "reasonable and necessary for stated purposes and beneficially used without waste." Applicants must also submit a drought management plan. These restrictions apply only to those well users diverting over 1500 AF/yr from the aquifer. The plan defines conservation as:

> "the development of other water resources; those practices, techniques, and technologies that will reduce the consumption of water, eliminate the loss or waste of water, maximize the efficiency in the use of water, prevent the pollution of water, or increase the recycling and reuse of water so that the demand for water from the Edwards Aquifer Underground River is reduced; and any other measure that would sustain or enhance the water supply to provide for future long-term needs."

Conservation methods are many and varied. They may be grouped by water use sector: residential, manufacturing, agriculture, and energy. Most involve new technologies, some of which are expensive to adopt. Before addressing specific methods, however, we must address the foundation for a successful conservation program—education and support programs.

Education is the most accessible and effective method of promoting water conservation. Any water conservation program should include methods for informing water users of ways to save water. Such methods for public education include television, radio, and newspaper announcements or advertisements. Public displays, school programs, speaker programs, and newsletters are other effective means of informing the public.

Support programs are the responsibility of the municipality or utility. An effective conservation program will be supported by incentives through rate structures. Appropriate water pricing is a direct and immediate method to encourage conservation. Effective rate structures will encourage wise use of water and discourage peak demands. Rate increases have only a short-term impact, however; water use usually returns to its previous level within a year.

With the foundations of education and pricing in place, water users can examine different methods of conservation to reduce their own costs. The most direct method is installation of water saving devices. These devices may include low flush toilets, water aerators, and high efficiency shower heads and appliances. In residential areas, conservation devices can be required in new construction, and financial incentives for retrofitting existing construction may be provided. Utilities, commercial businesses, and manufacturing centers would retrofit their buildings with water saving devices given the right financial incentives. In Austin, Texas, low-income housing retrofits replaced 5.0 gallon-per-flush with 1.6 gallon-per-flush toilets, reducing water use by about 25 gallons per day per person [CH2M Hill, 1986]. A university in Pennsylvania retrofitted its dormitories with high-efficiency water devices and saved 11 million gallons a year, about 20% of the University's total consumption. The Lenox Hotel in Boston replaced plumbing fixtures with high-efficiency fixtures in 220 rooms, reducing water demand by 40%.

Landscape irrigation is another area where great savings may accrue. Xeriscaping, or water-conserving landscaping, is a typical method of landscape irrigation reduction. A city or utility could encourage or require xeriscaping through education or ordinance. Xeriscape programs use native plants and grasses and utilize drip irrigation and other efficient irrigation mechanisms. In Mesa, Arizona, participants in landscape water efficiency programs receive rebates and use 40% less water.

Agricultural irrigation offers great opportunities to conserve. Efficient irrigation practices include low evaporation techniques, recirculation of tailwater, and soil moisture monitoring. Several successful irrigation plans have been implemented. In Lubbock, Texas, utility-financed irrigation efficiency projects resulted in 25 to 40% water savings and a reduction in the aquifer depletion rate from 1.4 million to .2 million gallons per year [Chaplin, 1991]. In Los Angeles, California, a water reuse program provides for irrigation by tertiary-treated effluent. And in Casper, Wyoming, the city repaired and lined a local irrigation canal in return for 2,000 AF/yr of water for municipal use.

Analyzing costs and benefits of different conservation programs can be difficult, because the savings are projected and hard to quantify. Costs and benefits of education programs and rate structure changes are difficult to predict because they rely so heavily on consumer behavior. Predicting the costs and benefits of technology changes, such as retrofit devices and water efficient appliances, is more direct.

The benefits and costs of various conservation methods have been estimated to be 10% of annual municipal and industrial demand [CH2M Hill, 1986] and this should be incorporated into water sources supply estimates. A 1988 plan estimated total conservation costs, as part of a comprehensive water management plan, to remain constant at $1.3 million a year through 2040 [Joint Committee, 1988]. Possible revenue sources for implementing a water management plan for the Edwards aquifer region have also been analyzed, and recommendations, including various fees, rate increases, taxes, and state or federal aid, have been made [Joint Committee, 1988]. Implementation mechanisms included education, policy changes, ordinances, market incentives, and government replacements.

## 3.5 TRADABLE PERMITS FOR WATER RIGHTS

The TWC plan delineates the method for establishing water rights by permit in Subchapter B [TWC, 1992]. The rules require that any "user" of Edwards aquifer water apply for a permit. A declaration of historical water use is considered to be a permit application. An applicant would also be required to submit a conservation plan and relevant fees by June 1, 1993. The TWC rules also establish interim authorization to use water without a permit until specified dates. The TWC retains the right to determine the extent and purpose of water diversion from the Edwards aquifer.

Currently, water rights in Texas operate on the principle of absolute capture. Absolute capture means that the owner of property rights to the land above an aquifer has rights to any and all water from the aquifer that he can pump from any point on his property. A famous example is the catfish farmer, Ron Pucek, of San Antonio. Pucek operates a catfish farm on the south side of San Antonio, and allegedly runs more water through his aquaculture system each year than do many large cities, all of it pumped from the Edwards aquifer. Under current Texas law, however, he has the right to use as much water as he can pump. Unfortunately, in this case the right of absolute capture provides no incentive to conserve water.

A market-based water rights plan for Texas groundwater would protect private property rights, while providing an incentive to use the scarce resources of the aquifer more efficiently. The government would be minimally involved in mandating the transition to market-based water rights. In this scenario, water rights would be assigned based on documented historical use. The transition, then, must be fast-acting, or people will increase water use immediately to establish historical use. After establishment, water rights could then be traded among users. The market system would ensure that the price of water rights reflect their true value.

The TWC plan outlines rules for trading water permits in Subchapter C, Conveyances [TWC, 1992]. The TWC must approve the sale of water rights, and thus impose the conservation and reuse requirements on the new user. The permit buyer must meet all requirements and prove the reasonableness and necessity of the water use just as the original permit applicant does.

There are several mechanisms for implementing the market-based water rights, including transferable water deeds, discount coupons, conservation investments trading, off-set programs, and option-to-buy contracts. The mechanisms could be used singly or in combination. Each addresses a different aspect of the market system applied to water rights.

First, to stimulate the market for water rights, the government could create a deeded right to pumping water from the Edwards aquifer. Economists have suggested that deeds in denominations of acre-feet be issued to aquifer water users based on historical use or proportionally by historical use. They suggest the constraint that the sum of the deeded rights not exceed the sustainable yield of the aquifer. Deeds to pumping rights would then be subject to market forces, such as buying, selling, and inheritance. Enforcement may be difficult; it would require monitoring water meters and issuing prohibitive fines in the event of violation [Chaplin, 1991].

At face value, deeded rights suggest a stable water level in the aquifer. Modifications to the deeded right mechanism must be made to accommodate changing water levels or variations in rainfall and recharge. The allotment of water to each deed certificate could be adjusted each year. Another suggestion is to issue two types of water deeds: interruptible and non-interruptible. Non-interruptible deeds would be set at levels of maximum pumping in a drought situation. Interruptible deeds would be issued to those well owners who have not exercised their right to pump water, like farmers who do not irrigate. Prioritizing the interruptible deeds could facilitate drought management of the aquifer [Emerson and Merrifield, 1992].

Second, a discount coupon system could be used to protect municipal water consumers from higher prices as a result of the market-based plan. Municipal water customers would be issued coupons for a certain amount of water at the average urban water price. Customers who use less than their allotment of coupons could sell or save their coupons, and customers who use more would have to pay a much higher price for the water used in excess of their allotment. The discount coupon system creates an active market for water conservation: consumers can save money by saving water [Emerson and Merrifield, 1992].

Third, farmers and government could participate in trading conservation investments for water. The EUWD, or some other "super district," could provide financing (in the form of grants, low-interest loans, or annual payments) to encourage farmers to either invest in water-saving irrigation equipment or convert to dry-land farming. In exchange, the Board would receive the rights to the water saved. An example of a workable conservation investments plan is the Metropolitan Water District (MWD) in California. The MWD faced a 400,000 AF/yr shortage of water to meet municipal water demands. A nearby irrigation district could save 450,000 AF/yr through expensive conservation and efficiency methods. The transfer of conservation finances for the water saved benefited both parties. This example could be modified to work in the Edwards aquifer plan. Water saved would not actually be owned by the investor, but would remain in the aquifer, guaranteeing more water availability.

Fourth, an offset program would require new users of water from the Edwards aquifer to offset the increased use by decreasing another use of the aquifer. For example, developers of new subdivisions in San Antonio could pay a farmer to take his land out of irrigation or pay residents for water saving changes such as xeriscaping. The developer would be required to file a report that the offset was a real savings of water use and that the offset will work into the future. Enforcement mechanisms would include fines and penalties to include offset costs and interest. The market works in the offset program by allowing entrepreneurs to decide which offset option is most cost-effective, rather than the government imposing a particular option.

Fifth, half-tap incentives could spur conservation and development by waiving fees for new homes that incorporate water saving devices. Such water saving devices may include xeriscaping, low-flush toilets, and water reuse systems. Municipalities charge developers fees to hook up a new subdivision to city water and electric facilities. If the market system works, developers save money on fees, and home buyers find water efficient homes attractive because of lower bills.

Sixth, the <u>option-to-buy contract</u> involves agricultural sellers and municipal buyers. For example, a 10-year contract between farmers and the Edwards Aquifer Water Board would assure that farmers would stop pumping if aquifer levels fall below a specified level. The contract could provide for a minimum payment during normal years and a much higher payment in drought years. The dry-year option provides payment to farmers to give up their option to pump during drought conditions. The beneficiaries of the option, water users whose use would have to decrease had the farmers not given up their options, are willing to pay the market determined price for the option to pump during the dry period [Emerson and Merrifield, 1992].

The market-based system offers many benefits to Edwards aquifer users. The most important, perhaps, is the fair and efficient allocation of the scarce resource. The price system in the free market ensures that water goes to its highest valued use. The market mechanism for bidding the price up or down lends a concrete dollar value to the subjective price of water. The market provides better information and offers the incentive to conserve. As water gets more expensive, reflecting its true value to society, people will tend to save money and thus conserve water.

## 3.6 CONCLUSION

The TWC plan for the Edwards aquifer calls for across-the-board reductions in water use by all economic sectors should a water shortage occur. Though this might seem the fairest way of implementing the plan, it does not appear to be the most economically efficient way. Since municipal and agriculture water use comprise the main water demand in the region, it would be wise to target these areas before targeting the manufacturing sector which has a great impact on the area's economy. Reduction in irrigation water use should be the first area targeted. Since farmers' water efficiency is expected to increase in the future, this would be a further impetus in this direction. The TWC plan's inclusion of economic incentives for farmers to improve irrigation practices is therefore a step in the right direction. Reduction in municipal water use mainly through conservation should be considered as the next step in the plan. Businesses which are not water intensive, especially those in the retail and trade industries, should be targeted next since they would not be greatly impacted by water restrictions. Manufacturing industries should be targeted for water restrictions only as a last resort.

The use of water curtailment is not an economically efficient way of reducing water use. Raising the price of water, thus giving it a greater economic value, during times of drought would economically encourage conservation and reduced water use. Thus, water would be allocated to its most economically beneficial use, and the economic impact of water reduction would be minimized.

The water conservation alternative which seems to offer immediate benefits at low costs is the use of reclaimed water in municipal and industrial irrigation. Use of reclaimed water in agricultural irrigation would involve greater costs, and more study must be done on the effectiveness and potential hazards of such a project. Artificial recharge is the second most viable alternative. It has been studied extensively and offers a low cost alternative to building water supply reservoirs. More studies must be done on vegetation management to determine its effectiveness.

Economic theory indicates that when the demand for water exceeds the supply of the Edwards aquifer, the price of water should rise. Our research indicates that population growth and urban development in San Antonio will continue to push water demand upward. The TWC plan to curtail demand is a necessary step in managing the Edwards aquifer. We feel, however, that economic incentive rather than government mandate is the most efficient way to reduce water demand. The shift to a market-based water rights system would allow the price of water to reflect the true cost of this scarce resource. A higher price on water will stimulate conservation, development of water-saving technology, and utilization of alternative water supplies.

# 4.0 ENVIRONMENTAL CONCERNS

Gregory B. Gates, Marcel G. Goemans, Petra Proesmans,
Daene C. McKinney, and David W. Watkins, Jr.

## 4.1 INTRODUCTION

Before one can effectively manage an aquifer, a clear understanding of its geological, biological, and hydrological characteristics, as well as its influence on the surrounding environment, is necessary. Also, maintaining minimum values for springflows and water quality is an essential part of any Edwards aquifer management plan. For these reasons, the geology of the aquifer is briefly discussed, including important hydrogeologic quantities and aquifer properties. Water quality data for the aquifer, and for streams influencing—or influenced by—the aquifer are analyzed. Available information on the required minimum springflows to sustain life in the springs, rivers and estuaries is analyzed and discussed. Also, the influence of decreased springflow from the aquifer on the water quality of the surface water, on the salt water intrusion in the Guadalupe River delta, and on the movement of the "bad water" line is discussed. The values for the required minimum springflows and the required water quality of this study are compared with the values provided by the TWC plan. Finally, the claim that the Edwards aquifer is an underground river will be checked with a list of physical conditions that need to be satisfied in order to call a body of water a "river."

## 4.2 GEOLOGY OF THE EDWARDS AQUIFER

As illustrated in Figure 4.1, the Edwards aquifer extends across three depositional provinces: the Maverick Basin, the Devils River Trend, and the San Marcos Platform [Sharp, 1990]. The aquifer in the San Marcos Platform is formed by rocks from the Edwards Aquifer Group, Person and Kainer Formations, and the overlying Georgetown Formation. These geologic formations can be subdivided as shown in Figure 4.2. The average thickness of the aquifer in the San Marcos Platform is about 75 m for the Kainer formation, 55 m for the Person Formation, and 6 to 20 m for the Georgetown Formation. The Devils River Limestone in the Devils River Trend is approximately 140 m thick. The aquifer thickness in the Maverick Basin is about 40 to 45 m for the West Nueces Formation, about 45 to 50 m for the McKnight Formation, and about 95 to 100 m for the Salmon Peak Formation [Hammond, 1986].

The dominant structural feature of the aquifer is a series of subparallel, northeastward-trending, steep-angle normal faults (Figure 4.3). Small grabens and horsts have formed which exert local control on groundwater movement [Maclay, 1991].

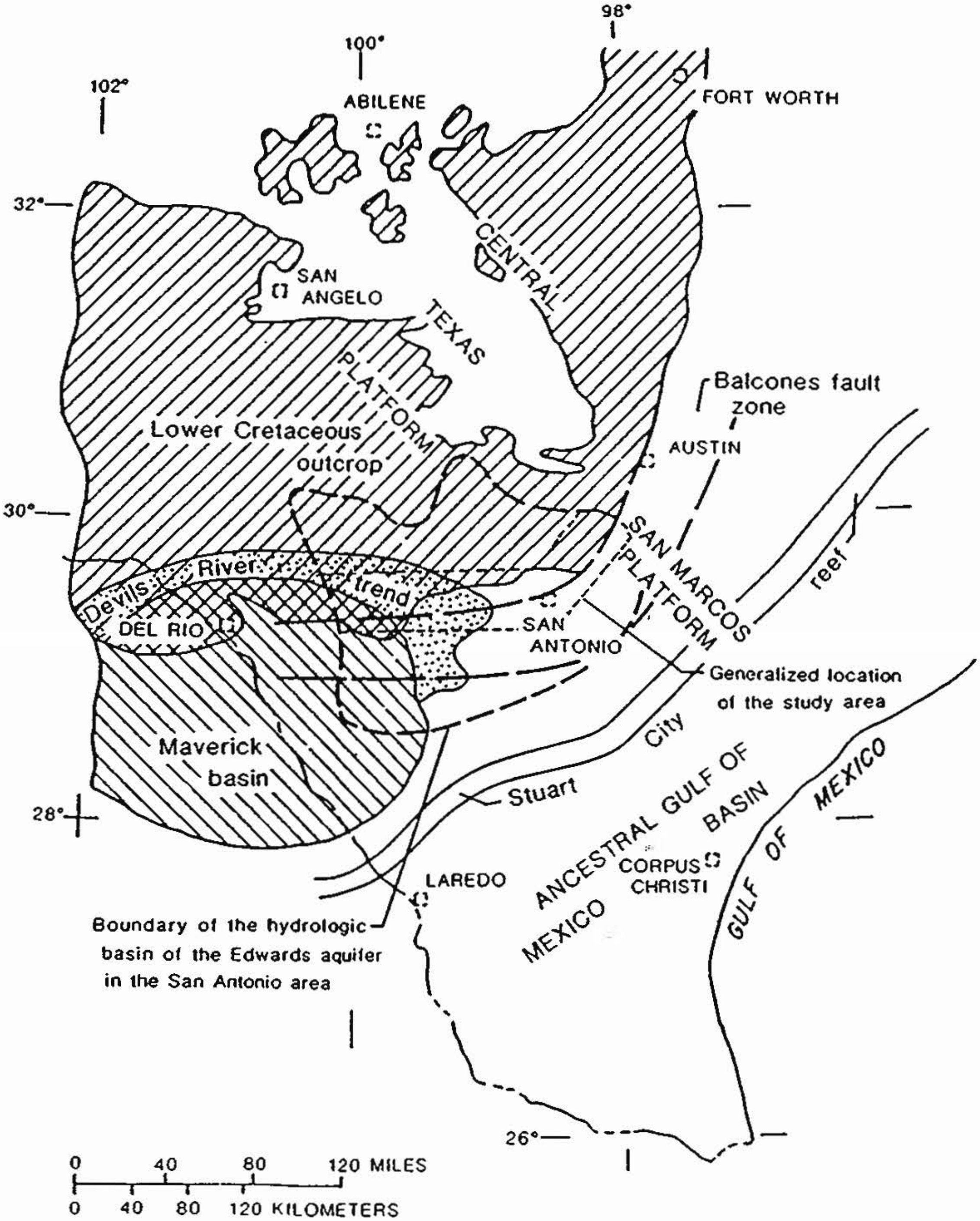



**Figure 4.1** Depositional Provinces and Geologic Structure of South Texas [Rose, 1972].

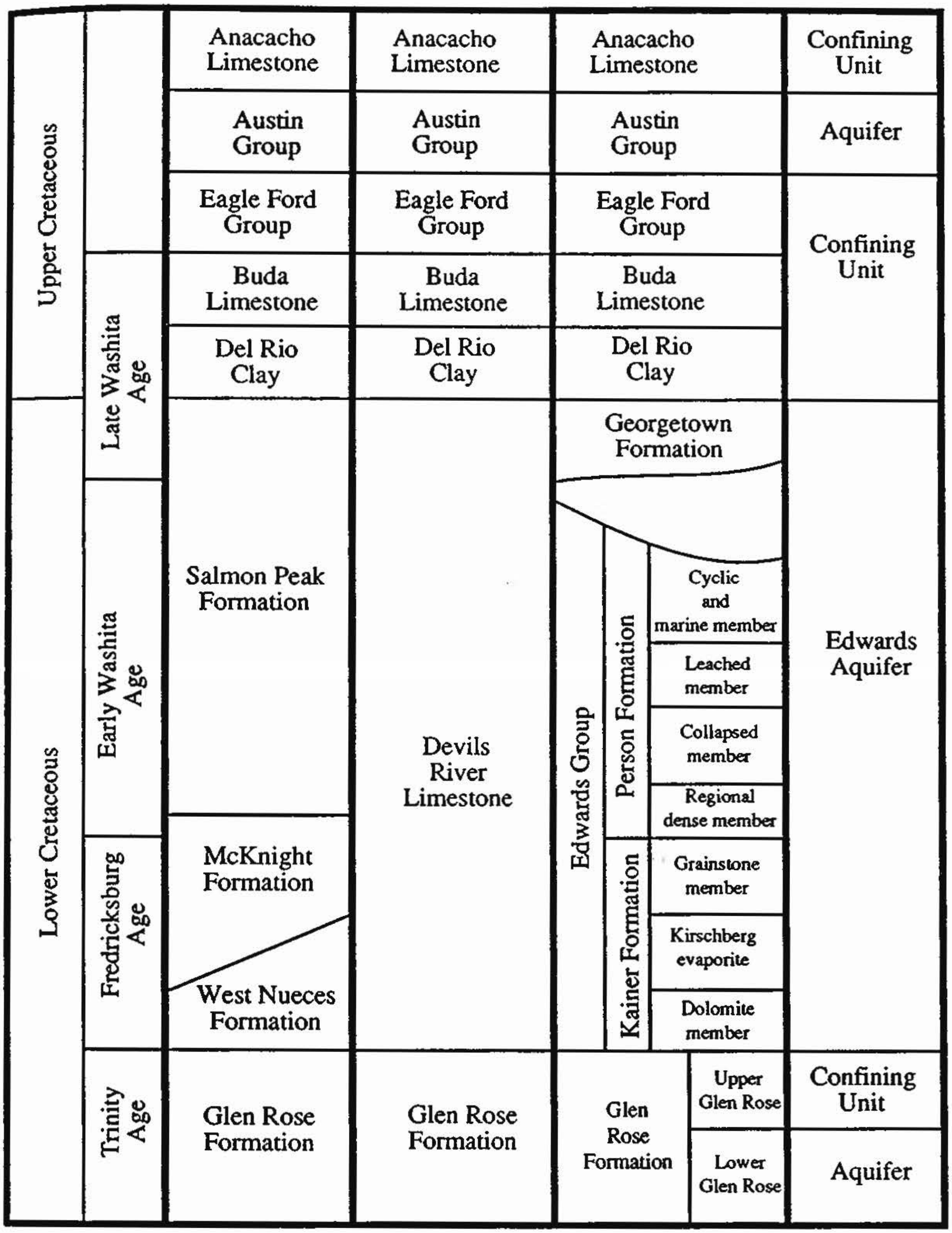



**Figure 4.2** Correlations of Cretaceous Stratigraphic Units in South Texas [Maclay, 1991]

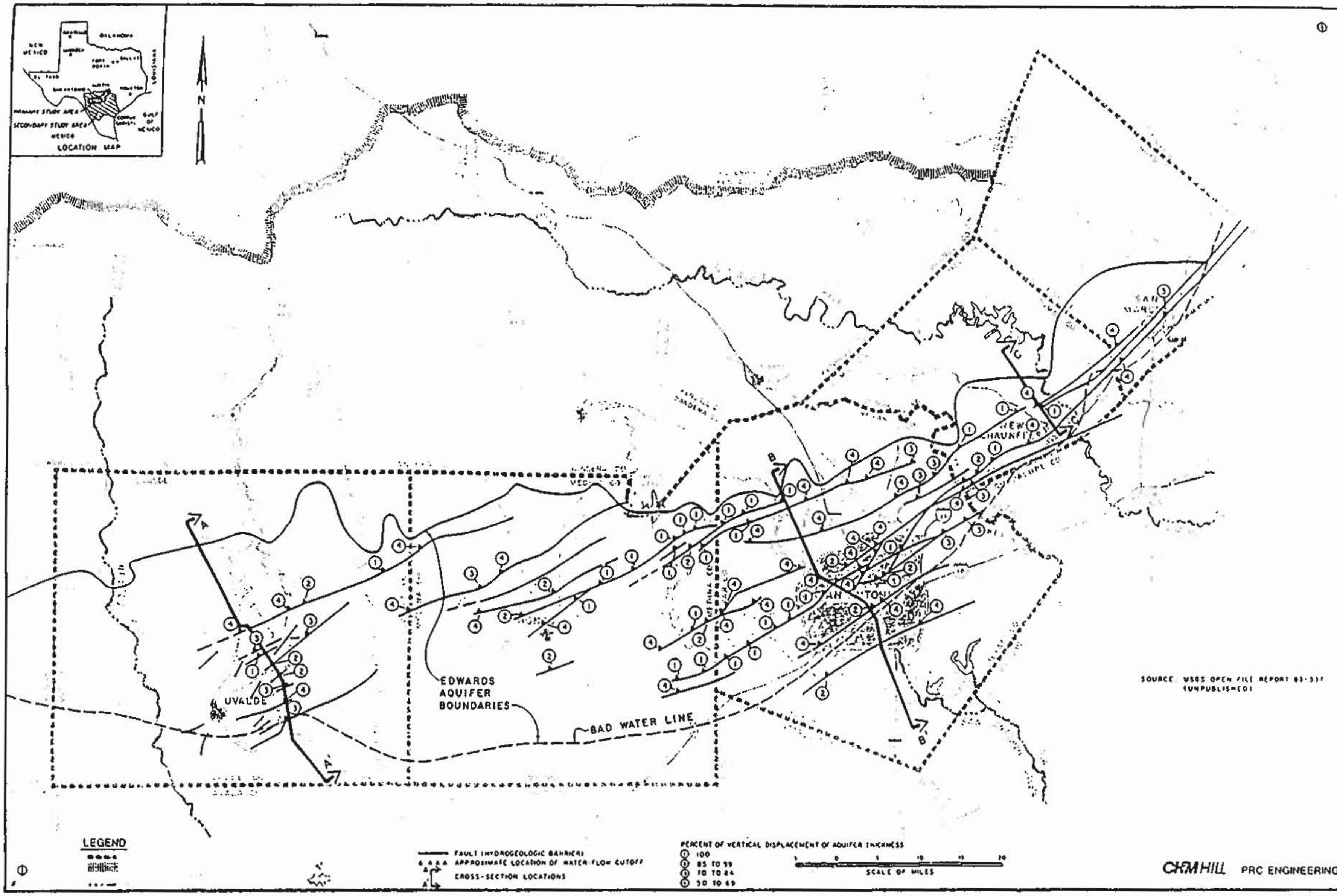
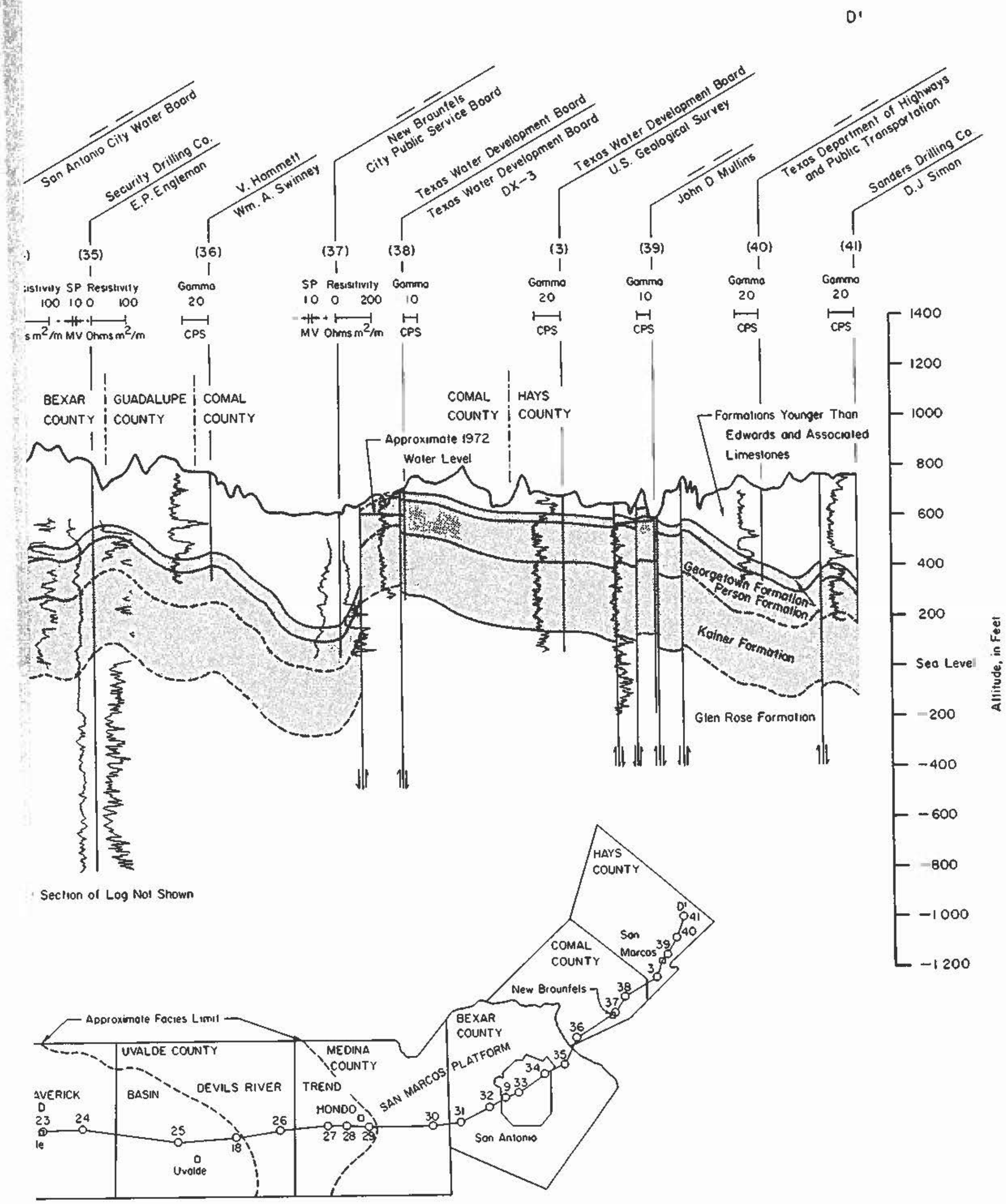



**Figure 4.3** Major Faults of the Edwards Aquifer Southern Segment [CH2M Hill, 1986]




roximate Areal Extent of Regional Geologic Elements are Taken From Rose (1972) and Field Notes bad-water zone, the appearance of the saline water aquifer is significantly different from that of the fresh water aquifer. Rocks in the bad - water zone are dolomitic, dark gray to dark brown, and contain gypsum, pyrite, celestite and unoxidized organic material. Rocks in the fresh-water zone are typically calcitic, highly recrystallized, light colored, and contain little or no organic material. Rocks in the bad - water zone have small interparticle, intraparticle, and matrix porosity, whereas rocks in the fresh-water zone have a well developed secondary and fracture porosity which has developed an integrated network of solution channels. Locally, faulting can control the location of the bad-water line by restricting the lateral movement of groundwater where fault displacement has placed into juxtaposition permeable strata opposite impermeable strata [Hammond, 1986]. Lower water levels in the aquifer can reverse the direction of the hydraulic gradient, thus causing the intrusion of saline water into the fresh water zone [USGS, 1987a]. This phenomenon has been observed in the Edwards aquifer north of Austin [Clement and Sharp, 1987].

Regionally, groundwater recharges the aquifer on the northern and northwestern margins and flows to the east and northeast to discharge either at major springs or to wells. The faults have created a highly anisotropic permeability field, and the direction of groundwater flow and the hydraulic gradient are not, generally, in the same direction. Groundwater is subparallel to the strike of the fault system, whereas the hydraulic gradient is generally downdip [Sharp, 1990].

In northern Medina County, the direction of groundwater movement is controlled by a series of northeastward striking fault barriers that divert groundwater to the southwest. In the northwestern part, groundwater moves to the south into the confined part of the aquifer, whereas in the southwestern part, the groundwater moves directly into the deeper, confined parts of the aquifer. In southern Medina County, the groundwater moves eastward into Bexar County. Groundwater movement in the unconfined (recharge) part of the aquifer is northeastward towards the narrow part of the aquifer, in general, but is southeastward in the area of Cibolo Creek (northeast Bexar County). Water in the unconfined part of the aquifer in Comal County moves to the southeast towards the Hueco Springs fault. Water in the confined fresh water zone of the aquifer moves along the downthrown side of the Comal Springs fault. In the southern part, groundwater in the confined aquifer moves northeastward through a narrow strip bordered by the Hueco Springs fault and the Comal Springs fault and is discharged at San Marcos Springs. Flow from recharge areas west of San Marcos moves southeastward to San Marcos Springs [Hammond, 1986]. Pumping seems not to alter the regional flow direction since most of the production wells are located east of the recharge zone, in the main stream path. However, small changes occur in the neighborhood of major wells [Maclay, 1991].

Recharge into the aquifer occurs in the outcrop area, primarily from streams draining the Edwards Aquifer Plateau and the recharge zone. During dry seasons, many of those rivers cease to flow once they cross the recharge zone (e.g., the Nueces River [USGS, 1983]). Direct infiltration of precipitation in the recharge zone is small compared to the recharge by streams. Stream recharge is enhanced by the fact that water can readily infiltrate the highly fractured and permeable carbonate rocks that occur along the streambeds. In order to sustain streamflow downstream from the recharge zone, an upstream flow rate of 0.10 $m^3/s$ is required for the Frio River, of 0.9 $m^3/s$ for the Nueces River, and of 1.2 $m^3/s$ for the Sabinal River (1 $m^3/s$ = 35.3 cfs). Nine major rivers contributing to the recharge of the aquifer are listed in Table 4.1.

Groundwater is discharged from the aquifer through man-made wells and natural springflow. A small amount is considered to be lost through intrusion into the bad-water zone. Six major springs are natural outlets of the aquifer and are listed in Table 4.2. From 1970 to 1985, the average rate of mining of the aquifer was approximately 7,000 AF/yr (the value in the TWC plan is 50,000 AF/yr). But for 1984, discharge exceeded recharge by 504,000 acre-feet [EUWD, 1987]. This indicates that we are in danger of depleting the transient storage of the aquifer (see below).

It is important to realize that the record drought was followed by a record wet period. This means that the consequences of the drought were minimized. Hence, using the drought of record might not adequately represent worst case conditions.

The average regional specific yield (effective porosity) of the Edwards aquifer in the San Antonio region is calculated to be 0.025. Individual estimates range from 0.010 to 0.030 [Maclay and Rettman, 1973]. The effective porosity of the Edwards aquifer is mainly of secondary nature [Maclay and Rettman, 1973]. This means that the bulk part of the transport of water occurs through caves, fractures, or honeycombed rocks. Estimates for the effective porosity for different cross sections of the aquifer are listed in Table 4.3. Effective porosities increase from west to east and are generally higher in the upper formations.

The secondary nature of the porosity explains why the flow rate of water through the aquifer is 50 to 500 times higher than in most other aquifers in Texas [Harden, 1988].

**Table 4.1** Water Balance for the Edwards Aquifer—Recharge

| Basin | Average (AF/yr) | Range (AF/yr) | Reference |
|---|---|---|---|
| W. Nueces - Nueces | 100,900 (1934-85) | 8,600-411,300 (1934 & 1935) | EUWD, 1986-87 |
| Dry Frio - Frio | 110,400 (1934-85) | 4,200-300,000 (1956 & 1958) | EUWD, 1986-87 |
| Sabinal | 37,900 (1934-85) | 600-223,000 (1955 & 1958) | EUWD, 1986-87 |
| Seco - Hondo - Verde - Medina | 92,900 (1934-85) | 4,400-286,000 (1953 & 1973) | EUWD, 1986-87 |
| Medina Lake | 60,000 (1934-85) | 6,300-104,000 (1956 & 1960) | EUWD, 1986-87 |
| Helotes - Salado | 65,000 (1934-85) | 2,000-237,200 (1956 & 1973) | EUWD, 1986-87 |
| Cibolo - Dry Comal | 100,800 (1934-85) | 2,200-397,900 (1956 & 1957) | EUWD, 1986-87 |
| Blanco | 36,700 (1934-85) | 8,200-85,900 (1956 & 1975) | EUWD, 1986-87 |
| San Geronimo Dam | NO DATA | NO DATA | Buchett et al., 1986 |
| **Total** | **604,500** (1934-85) | **43,700-1,711,200** (1956 & 1958) | USGS, 1987b EUWD, 1986-87b |

**Table 4.2** Water Balance for the Edwards Aquifer—Discharge

| Discharge Point | Average (AF/yr) | Range (AF/yr) | Reference |
|---|---|---|---|
| Comal Springs | 208,500<br>(1940-85) | 28,000-295,400<br>(1956 & 1975) | CH2M HILL, 1986 |
| San Marcos Springs | 111,800<br>(1940-85) | 47,600-167,400<br>(1956 & 1975) | CH2M HILL, 1986 |
| Leona Springs | 17,000<br>(1980)<br>15,015 (1) | 0-159 AF/D<br>(3) | USGS, 1985 |
| San Antonio Springs | included in (1) | 0-295 AF/D<br>((2) & 1977) | USGS, 1985 |
| San Pedro Springs | included in (1) | 0-34 AF/D<br>((2) & 1977) | USGS, 1985 |
| Hueco Springs | 26,500<br>(1944-74) | 0-94,800<br>(often & 1968) | GBRA, 1988 |
| **Total for Springs** | 320,000<br>(1934-82)<br>350,000<br>(1936-86)<br>360,000<br>(1945-81) | 356,000-575,000<br>(1956 & 1977) | CH2M HILL, '86<br>USGS, 1985<br>Maclay, 1991 |
| Pumpage for Industry | 16,500<br>(1985) | NO DATA | GBRA, 1988 |
| Pumpage for Irrigation | 203,100<br>(1985) | NO DATA | GBRA, 1988 |
| Pumpage for Municipal | 263,700<br>(1985) | NO DATA | GBRA, 1988 |
| Pumpage for Misc. | 39,200<br>(1985) | NO DATA | GBRA, 1988 |
| **Total for Pumpage** | 417,000<br>(70-86)<br>522,500<br>(1985) | NO DATA | GBRA, 1988<br>USGS, 1985 |
| **Total Discharge** | 767,000<br>(1970-86)<br>856,500<br>(1985) | NO DATA | USGS, 1985<br>Harden, 1988 |

(1) [Buchett et al., 1986].

(2) No springflow 75% of the time.

(3) No years given.

**Table 4.3** Effective Porosity of the Edwards Aquifer [TDWR, 1979b]

| | Estimated Effective Porosity (% by Volume) | | | | |
|---|---|---|---|---|---|
| County | Upper Section | Middle Section | Lower Section | Weighted Average | Glen Rose Formation |
| Kinney | 9.8 | 1.0 | 1.2 | 7.4 | 2.0 |
| Uvalde | 3.5 | 0.5 | 0.0 | 2.3 | 1.2 |
| Medina | 9.3 | 5.1 | 4.6 | 6.5 | 0.2 |
| Bexar | 12.2 | 2.2 | 6.4 | 8.6 | 4.7 |
| Comal | 8.4 | 6.2 | 8.0 | 8.1 | 5.1 |

Estimates for the flow rate range from 0.6 to 9.4 meters per day for different parts of the aquifer. This results in a residence time of 20 to 35 years for water in the aquifer [Hammond, 1986].

Since the Edwards aquifer is a carbonate aquifer, characterized by a heterogeneous and anisotropic nature, the transmissivity is hard to specify. In general, areas to the west in the McKnight and West Nueces Formations have low values of transmissivity, while in areas to the east, transmissivities are much higher. Estimates range from 18,600 $m^2/d$ to 186,000 $m^2/d$ [Hammond, 1986] or from 1,245 $m^2/d$ to 124,500 $m^2/d$ [USGS, 1987b] for the whole aquifer, and from 0.22 $m^2/d$ to 3540 $m^2/d$ for the aquifer in the San Marcos area [Ogden et al., 1986].

The bulk storage within the interconnected openings in the freshwater part of the Edwards aquifer in the San Antonio region is estimated to be 25 to 55 million acre-feet. Most is stored within the smaller openings in the rock matrix in the confined aquifer and not in the larger vugular openings. This "dead volume" is water stored within the aquifer at elevations below the elevation of the outlet of Comal Springs. Transient storage is the storage that sustains springflow during periods of no recharge. It is continuously changing in proportion to the difference between recharge and discharge. The transient storage is the storage of water in the aquifer between the record low and record high, and is estimated to be 3 million acre-feet.

The practical sustainable yield of the aquifer is the long-term average recharge [Maclay, 1991]. However, if the aquifer is treated as an underground river, the historic minimum recharge would be the "firm yield." This is only 43,700 AF/yr (Table 4.1). Because of the storage characteristics of the Edwards aquifer (the "transient storage"), the "firm yield" might be better estimated when the aquifer is envisioned as a reservoir with a storage capacity of 3 million acre-feet (= the transient storage). Historical recharge and discharge data would then enable us to calculate a "firm release." Based on model simulations done by the TWDB, the maximum allowable pumpage during a drought is estimated at 250,000 AF/yr [TWDB, 1992]. Under those conditions, Comal Springs would discharge 23,000 AF/yr, and San Marcos Springs would discharge 110,000 AF/yr. Hence, the firm yield of the aquifer is estimated at 383,000 AF/yr. This is well below the 603,000 AF/yr as suggested by Maclay, but well above the firm yield of the "underground river."

## 4.4 CONSIDERATIONS REGARDING THE MANAGEMENT PLAN

The TWC management plan [TWC, 1992a] calls for a minimum flow in Comal Springs of 100 $ft^3/s$, at least 80% of the time. This would translate to a minimum annual flow of 57,900 AF/yr (80% of the time at 100 $ft^3/s$, 20% of the time no flow). Based on the discussion above, we see that this leaves about 200,000 AF/yr for human use (with a flow at San Marcos Springs of 110,000 AF/yr). This is much less than the pumpage allowed under the management plan. There is only 400,000 AF/yr available for pumpage if we accept that the "firm yield" of the aquifer is equal to the average annual recharge. This is probably not a realistic approach, and alternative water resources need to be investigated.

Increasing pumpage from the aquifer and continuous flowing of the springs might both be satisfied by springflow augmentation [TWC, 1992a]. Springflow augmentation means that water will be pumped from the dead storage volume, or some other source, in order to keep the springs flowing. This could entail "mining" of the aquifer, which is obviously not a long term solution. Another possibility would be additional recharge as provided by Medina Lake [TWC, 1992a]. The U.S. Army Corps of Engineers has conducted a comprehensive survey of the possible locations of Edwards aquifer recharge structures. Although additional recharge will certainly decrease the depletion rate of the aquifer, it probably will not solve the problem completely. It has been estimated that the total additional recharge, if all the proposed recharge structures are implemented, will be 69,000 AF/yr [Fisher, 1991]. Possible drawbacks include the following: (a) increased risk of contamination of the aquifer with heavy metals and organic chemicals, (b) less surface water availability downstream of the recharge area, (c) destruction of stream habitat, and (d) cost [Fisher, 1991]. A third possible measure is lowering groundwater levels in strategic locations to enhance infiltration from other aquifers or from rivers.

Based on the discussion above, it might be worthwhile to look for alternative water resources (e.g., construction of reservoirs). These reservoirs need to be constructed downstream of the recharge zone. Reservoirs upstream of the recharge zone can cause a decrease in recharge of the aquifer. Hence, the effects of a decrease in groundwater use would be offset by a decrease in recharge.

## 4.5 WATER QUALITY OF THE EDWARDS AQUIFER

A large data base on Edwards aquifer water quality is available because water quality has been monitored on a regular and frequent basis [USGS, 1987b; Ogden et al., 1986]. Since most of the water in the Edwards aquifer comes from the Edwards Aquifer Plateau, which is mainly undeveloped forest and range land, low contamination levels can be expected. This indeed has been found in most of the studies. The contamination that occurs is limited to the unconfined area [USGS, 1987b] and to uncased or defective wells [Clement, 1989].

Volatile organic compounds have been detected in a few wells, with concentrations ranging from 1 to 5 mg/L [EUWD, 1983, 1990]. Trihalomethanes have been found in concentrations ranging from 0.60 mg/L to 6.4 mg/L, and chlorinated hydrocarbon concentrations ranging from 0.2 to 7.4 mg/L. In most water quality surveys of the Edwards aquifer, none of the above were detected [EUWD, 1990; USGS, 1987b; TDWR, 1979a]. The presence of nitrate has been studied intensely [Browning, 1977; USGS, 1985, 1987b]. It seems that the nitrate concentration is highly dependent on the recharge rate [Browning, 1977]. Concentrations range from 0 to 15 mg/L, with the lower concentrations appearing in the lower part of the aquifer. Bacteria counts are very low in general, except for the San Marcos area where counts of 400 colonies per 100 mL have been found. This high contamination level has been attributed to broken sewer lines [EARDC, 1986].

In conclusion, we can say that the potential for contamination of the Edwards aquifer from existing human activity is limited. Urbanization of the area north of San Antonio, in the recharge zone, poses the risk of recharging the aquifer with contaminated runoff water. In addition, many landfills and storage tanks are near the recharge zone. Leakage has been minimal so far, but this is likely to change over time [USGS, 1987a, b]. Over-pumping the aquifer can cause intrusion of saline water from the bad-water zone, thus threatening the water quality in many public wells located near the transition zone [Clement, 1989].

A successful Edwards aquifer management plan should address the potential for aquifer contamination, including restricting human development in the catchment area and recharge zone and close monitoring of landfills and storage tanks.

## 4.6 INFLUENCE OF REDUCED SPRINGFLOW AND STREAMFLOW ON WILDLIFE IN THE RIVER BASINS

Why is this springflow so important? First of all, Comal and San Marcos Springs make up about 25% of the baseflow of the Guadalupe River under average weather conditions and up to 75% during drought conditions [Thornhill, 1988]. Hence, springflow is crucial to providing the water demand for municipal, industrial, and recreational use and to sustaining wildlife in and around the river basins. Furthermore, a minimum river flow has to be maintained to prevent increasing pollution (by lack of dilution) and to prevent intrusion of salt water into the bays and estuaries. Another reason why springflow is emphasized in Edwards aquifer management is that the amount of springflow reflects the water level in the aquifer, and thus tells us about the available water storage in the aquifer.

The aquifer and springs are known to have a diverse number of highly adapted aquatic species. The Edwards aquifer is considered one of the most diverse subterranean aquatic ecosystems in the world [Harden, 1988]. A decreased water level in the aquifer jeopardizes this unique fauna because of a reduced springflow or because of more concentrated pollutants.

In the following paragraphs, the importance of a minimum instantaneous springflow to protect wildlife in and downstream from the springs will be discussed. The need for a minimum flow level has been expressed by several organizations. The Sierra Club clearly asked for—and the federal district court has ordered—minimum flow levels at San Marcos and Comal Springs in order to ensure the survival of several species protected under the federal Endangered Species Act [Sierra Club vs USFWS, 1992, 1993]. The Sierra Club was supported by the Guadalupe-Blanco River Authority, which wants to protect its primary water source from going dry, and by the cities of San Marcos and New Braunfels officials, who are concerned about the potential loss of tourism associated with the springs.

### 4.6.1 Fauna in the Aquifer

Unlike other aquifers in Texas, the Edwards aquifer is known to be the habitat of about 40 aquatic species. Organic material, including plant and animal remains, enters the aquifer along with recharge. This organic material is a food source for the organisms living in the aquifer, which include bacteria, crustaceans, flat worms, snails, beetles, salamanders, and catfish. Through thousands of years of living in the darkness, the aquifer organisms have developed characteristics unlike their surface relatives. Eyes have often degenerated or disappeared, and pigment in the skin is virtually absent. Typical examples are the Texas Blind Shrimp, the Texas Blind Salamander, and the Toothless Catfish [EUWD and EARDC, 1981].

These species could be threatened if the water level in the aquifer drops. A local depletion of water can damage their unique habitat, but a more likely threat is the change of the chemical composition of the water because of the lower flow. These species are very sensitive to minor changes in water characteristics, such as constituent concentration or temperature. Reduced flow in the aquifer may induce higher concentrations of constituents which are harmful to these species.

The minimum required water level and associated flow rates to protect these species will vary locally, but one can assume that a water level that ensures species habitat is protected by flow which provides sufficient dilution of pollutants [EUWD and EARDC, 1981].

### 4.6.2 Wildlife In and Downstream of the Springs

The Guadalupe River and its tributaries (San Marcos and Comal Rivers) depend mainly on the springflow of San Marcos and Comal Springs for their flow in dry years. Therefore, several environmental issues are related to the problem of decreasing springflow. These include the legal and environmental issue of endangered species, the impact on wildlife habitat and vegetation, the increasing problem of water quality, salt intrusion in bays and estuaries, and the question of recreational water use. Some of these issues will be discussed here.

<u>Endangered species:</u>

Five species, listed as "endangered species," live in or downstream from the springs:

- Fountain Darter (*Etheostoma fonticola*) found at Comal Springs (in the spring runs and above Landa Lake, in Landa Lake, and in a segment of the Comal River downstream of Landa Lake) and at San Marcos Springs (in Spring Lake and a segment of the San Marcos River downstream of Spring Lake).

- San Marcos Gambusia (*Gambusia georgei*) found in a segment of the San Marcos River downstream of Spring Lake. None have been found in the wild since 1985.
- San Marcos Salamander (*Eurycea nana*) found in the spring openings at San Marcos Springs and in the spring runs.
- Texas Wild Rice (*Zizania texana*) found in Spring Lake and a segment of the San Marcos River downstream of Spring Lake.
- Texas Blind Salamander (*Typhlomolge rathbuni*) found underground in the Edwards aquifer in a relatively small segment of the aquifer near San Marcos Springs.

Although the fountain darter and the San Marcos salamander have been reported in the past to occur in the Comal River and Springs, a field investigation [Espey, Huston and Associates, 1975] did not yield any samples of these two species. Most likely, these two species have disappeared, and a further depletion of springflow could eliminate the other endangered species as well. The survival of these species largely depends on the maintenance of critical springflow, water temperature, and water quality [CH2M Hill, 1986].

Two new, rare and possibly endangered species, the dryopid beetle and the riffle beetle, have been discovered in Comal Springs. Other than these endangered species, which have their habitat in the springs or related streams, other endangered species occur in the area, like the American alligator, the bald eagle, and the red wolf [CH2M Hill, 1986]. These species could indirectly be affected by a cessation of the springflow. Probably, they could be most affected by a decrease in their prey population.

<u>Wildlife habitat and vegetation:</u>

As previously mentioned, the flow of the Guadalupe River and its tributaries is heavily reliant on springflow during dry periods. As long as regulations do not relate pumping rates to water level in the aquifer, a continuous springflow is not assured for the future. Dry periods normally increase the water demand and thus the pumping of the aquifer. To ensure a continuous and instantaneous springflow, and thus streamflow in dry periods, a minimum water level in the aquifer should be maintained. Some major questions need to be answered:

*What is the impact of a reduced streamflow on the aquatic ecosystem?*

As a result of a prolonged period of reduced flow, the following changes in the river bed may occur:

- change in channel morphometry
- current velocity decrease, and thus more siltation
- more bottom coverage by vegetation, and thus less clear rock and gravel
- absolute temperature increase and more temperature fluctuations
- decrease in water quality

These changes have their impacts on habitat and or survival of the living species in the following ways [Espey, Huston & Assoc., 1975]:

- redistribution of microhabitats
- habitat losses for most species
- gain of new habitat for those species that are adapted to the new conditions

Generally, a decreased streamflow can be survived by those species able to change their habitat in location and/or conditions. It is obvious that the fish population, for example, will be seriously damaged as soon as streamflow stops, while other species can survive a longer drought by migrating to another location.

One may conclude that a prolonged period of reduced streamflow, or even a cessation of streamflow, will be unfavorable for the original wildlife population and vegetation, but it can create new habitats for different species.

*What are the required flows?*

Few studies have attempted to quantify required flows for the springs. The studies that did so recommend the following minimum flow values (Table 4.4). Some comments should be made regarding this table:

- In proposing minimum springflows to maintain (aqua)biota, only a few consequences of a reduced streamflow have been considered. Primarily, the reduction of the water quantity and temperature changes have been taken in account. Changes in water chemistry, in bottom vegetation, slope of riverbed, etc., have not been considered. These "secondary" consequences could nevertheless be substantial and detrimental.
- When talking about maintaining the aquatic ecosystem in the river basin, one should keep in mind that the first condition for the survival of an aquatic system is a flowing stream. Thus, annual average flows are somewhat meaningless if continuous flows are not maintained.

Instantaneous daily flows have been shown to be a major factor in the determination of minimum springflow recommendations [Espey, Huston & Assoc., 1975]. The following springflow limits have been proposed for the San Marcos River (other things being equal):

- a minimum instantaneous (daily) flow of 40 cfs
- a monthly average flow of 80 cfs
- a minimal average flow in excess of 100 cfs

**Table 4.4** Minimum Springflow Values to Sustain Biota [CH2M Hill, 1986]

| Spring System | Purpose | Annual Avg. AF/yr | Annual Avg. cfs | Minimum Month cfs | Source |
|---|---|---|---|---|---|
| San Marcos | 1. Maintenance of biota and recreation | 54,000 | 75 | - | 1 |
| | 2. Maintenance of aquatic biota | 72,000 | 100 | 80 | 2 |
| Comal | 1. Maintenance of biota and recreation | 54,000 | 75 | - | 1 |
| Both | 1. Maintenance of biota and recreation (% of historic) | 108,000<br>33% | 150 | - | 1 |
| | 2. Meeting downstream consumptive water rights diversions (% of historic) | 320,000<br>100% | varies | - | 3 |

1. USBR, 1978
2. Espey, Huston & Associates, 1975
3. Espey, Huston & Associates, 1986

However, these values do not necessarily provide a safe buffer against increased contamination. Previous studies have concentrated primarily on two organisms (*E. fonticola* and *P. arca*), but results can be extrapolated for the whole aqua-system.

To make a general statement about the minimum required springflow to maintain the entire aqua ecosystem, one should know the consequences of a reduced flow on all the species of the ecosystem, a difficult goal to achieve. A safe minimum flow may be an instantaneous springflow of 100 cfs. Even in very dry periods, this springflow would provide enough streamflow to sustain virtually the entire aquatic ecosystem.

## 4.7 BAYS AND ESTUARIES

Bays and estuaries act as transition zones between saline and freshwater conditions. An estuary is defined as "a body of water in which river water mixes with and measurably dilutes sea water" [Reid, 1961]. The unique conditions that occur in an estuarine system combine to form "highly variable environmental conditions" that are quite different from those of lakes or rivers [Reid, 1961]. As with any ecosystem that has developed over very long periods of time, an estuarine environment could be adversely affected by relatively sudden changes in the conditions that have produced that environment. The cessation of springflow from the Edwards aquifer may present such a scenario for the San Antonio Bay system.

The San Antonio Bay system, including Mission Lake, Guadalupe, Ayres, San Antonio, Mesquite, and Espiritu Santo Bays, acts as a buffer between freshwater flowing in the Guadalupe River and the saline conditions in the Gulf of Mexico [Espey, Huston & Assoc., 1986]. As noted in the introduction to this chapter, a significant portion of the freshwater flow in the Guadalupe River has as its source springflow from the Edwards aquifer. Therefore, changes in aquifer springflow discharge rates could potentially affect the downstream estuarine system.

In response to the possible downstream effects on the bays and estuaries of the current management of the Edwards aquifer, the TWC has included consideration of the bays and estuaries in their proposed management plan. The TWC's recently adopted regulations for managing the Edwards aquifer [Chapter 298, "Edwards Aquifer Underground River," §§298.1-298.7, 298.11-298.20, 298.31-32, 298.41-42, 298.51, and 298.61] state that "The commission intends to manage the Edwards Aquifer Underground River water rights so that they are not subordinate or superior to any downstream water rights." [p. 40, Chapter 298, TWC Regulations]. The TWC has also made providing for the bays and estuaries one of the primary reasons for their regulation. More specifically, they maintain that "Freshwater inflows provided by the river [Guadalupe] to the bays and estuaries are critical to the maintenance of estuarine habitat" [p. 9, Chapter 298, TWC Regulations].

In this section, some of the issues involved in considering the bays and estuaries (namely San Antonio Bay) in an Edwards aquifer management plan, including those raised by the TWC, will be considered. First, because the majority of the freshwater inflow to the San Antonio Bay system arrives from the mouth of the Guadalupe River, the current condition of San Antonio Bay will be considered. Included in this consideration will be the possible consequences of taking no action to change the current management of the aquifer. Second, the TWC management plan for the Edwards aquifer will be considered, including some possible consequences of the plan. And third, some researchers' estimates of required inflows for the bay system for maintenance of the ecosystem will be considered.

### 4.7.1 Present Situation

San Antonio Bay receives an average total annual freshwater inflow of approximately 2,690,000 acre-feet. This inflow is made up of flow from the Guadalupe

River, which includes flow from the San Antonio River (which like the Guadalupe is partially augmented by springflow from the Edwards aquifer), precipitation, and local runoff. The San Antonio River flow accounts for approximately 30% of the Guadalupe River's inflow to the bay [Lowry, 1958]. The Edwards aquifer contributes approximately 360,000 AF/yr to these rivers, and thus contributes approximately 13.4% of the total gross freshwater inflow to the bay. Precipitation accounts for 440,000 AF/yr of inflow, while local runoff accounts for approximately 460,000 AF/yr. The contribution to freshwater inflow of each source is presented in Table 4.5.

**Table 4.5** Freshwater Inflow to San Antonio Bay [CH2M Hill, 1986]

| Source | Inflow (AF/yr) | % of Total Inflow |
|---|---|---|
| Guadalupe River | 1,304,000 | 48.5 |
| San Antonio River | 485,400 | 18.0 |
| Precipitation | 440,000 | 16.4 |
| Local Runoff | 460,000 | 17.1 |
| **Edwards aquifer** | **360,000** | **13.4** |
| Total | 2,689,400 | 100.0 |

More water evaporates from the bay each year than precipitates. Thus, the contribution of the Edwards aquifer to the total average net annual inflow to San Antonio Bay is probably larger than that suggested by 13.4% of the average gross annual. Likewise, in drought years the Edwards aquifer has made up as much as 70% of the flow in the contributing streams [TWC, Chapter 298, 1992b]. Assuming drought conditions throughout the Guadalupe River basin, the contribution of the Edwards aquifer to the bays would likely approach 40% (based on a 66.5% contribution by the streams and equal reduction in inflow quantities). In fact, as can be seen in Figure 4.5, during the drought of record which occurred in 1956, flow from the Edwards aquifer constituted nearly 30% of the inflow to San Antonio Bay.

An estuary is a mixture of fresh and salt water that has a variable but stable overall salinity; the plants and animals that inhabit the estuary are adapted to these conditions [Reid, 1961]. For the same reasons that a freshwater fish cannot survive in a salt water environment, plants and animals that have adapted over time to live in an estuary cannot be thrust either into fresh or salt water environments and expected to survive. In fact, "... salinity constitutes a striking example of an environmental factor which limits organisms..." [Reid, 1961]. As freshwater inflow into San Antonio Bay is the mechanism

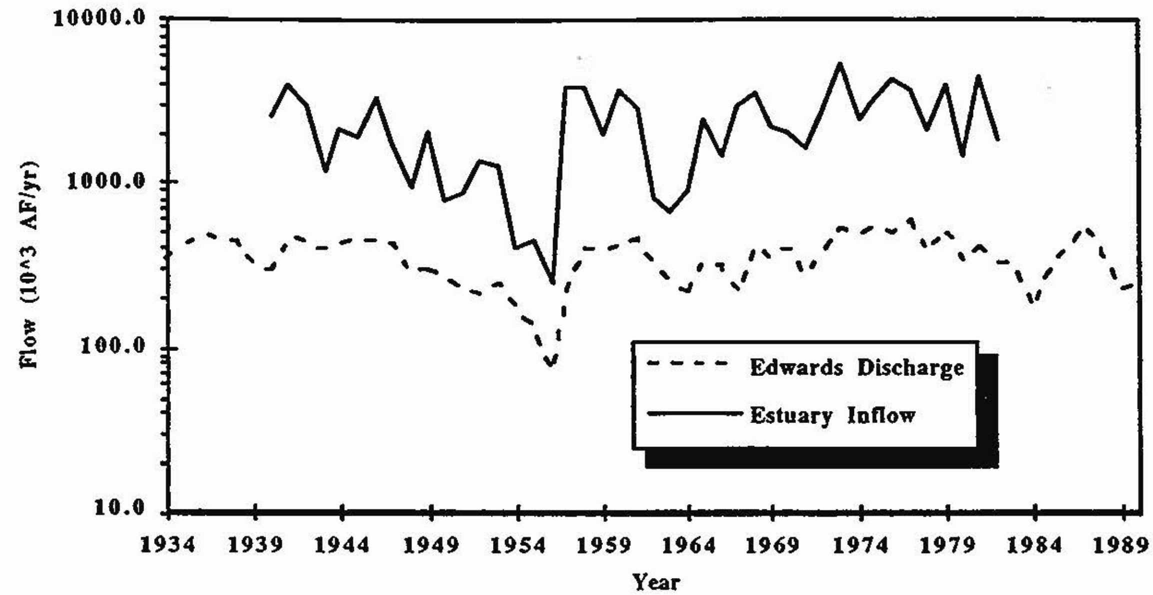



**Figure 4.5** Flow Variation for the Edwards Aquifer and Inflow to San Antonio Bay [Espey, Huston & Assoc., 1986; EUWD, 1991]

by which salinity is reduced and "...river flow is the prime source of fresh water...", the marine estuary environment depends on river flow, and thus the Edwards aquifer, for survival [Childress et al., 1975].

River inflows are also one of the primary sources of nutrients for San Antonio Bay. River flow accounts for the inflow of approximately 22 metric tons of phosphorous and 26 metric tons of nitrogen into the bay per day [Childress et al., 1975]. River inflow also provides greater dissolved oxygen concentrations in two ways. First, because of changing activity coefficients and increasing ion concentrations, the solubility of oxygen decreases as the water becomes more saline. Thus, the low salinity fresh water influent provides a significant amount of dissolved oxygen to bay life. Second, the freshwater inflows dilute the estuary system so that oxygen becomes more soluble within the estuary. The freshwater flowing into the bay also tends to flush pollutants from the bay system [Powell, 1977]. Based on these relationships, the importance of Edwards aquifer flow to the estuarine ecosystem has been established.

Studies on commercial shellfish and finfish production [Childress et al., 1975; Powell, 1977] have confirmed this relationship. Statistical analysis of data on finfish harvest from 1962 to 1976 have shown that 64.2% of the finfish harvest's yearly variation was explained by fluctuations in the three year average freshwater inflow during critical seasonal growth periods [Powell, 1977]. Over the same time period, variations in commercial shellfish harvest were explained 43.3% of the time by variations in springtime freshwater inflow [Powell, 1977]. Likewise, production of white shrimp was noted to have been highest during above average inflow periods and lowest during below average inflows [Childress et al., 1975]. The greatest concentrations of blue crab were generally found in the lowest salinity concentration areas of the bay (i.e., river mouth), and they have been most widely abundant during the years of highest inflow [Childress et al., 1975]. Brown shrimp were the only species tested that were more abundant in the more saline portions of the bay, but their production was still greatest during high inflows of freshwater [Childress et al., 1975]. The primary difficulty with the type of data presented above is the lack of control over circumstances [Espey, Huston & Assoc., 1986]. The effects of disease, weather, and economics (of fishing) are not accounted for. However, it seems probable that these results show a general trend and can be extrapolated to other species in the bay to represent the health of the entire ecological system. Table 4.6 shows the general effect on several commercially viable species in the bay.

**Table 4.6** Commercial Species Susceptibility to Inflow Variation [Powell, 1977; Childress et al., 1975]

| Species | Effects |
|---|---|
| Shellfish | 43.4% of variation in production is associated with inflow variation |
| Finfish | 64.2% of variation in production is associated with inflow variation |
| White Shrimp | low production corresponds to low inflow, seasonal variation is important |
| Brown Shrimp | high production seems to corresponds to high inflow |
| Oysters | inflow should be between 0.6 and $2.8 \times 10^6$ acre-feet |
| Blue Crab | young prefer low salinities, highest production in high inflow years |

A lack of management of the Edwards aquifer will eventually lead to a radical change in these conditions. As noted in the TWC plan, current average annual discharge (springs plus pumping) from the aquifer exceeds average annual recharge to the aquifer by 50,000 acre-feet. The plan goes on to state "At current levels of water use, the Edwards aquifer has become highly vulnerable to drought." [TWC, 1992a]. Since the bay system is thought to be in a healthy state at present, it is suggested that any alterations to the historic sediment loads will degrade the system [Childress et al, 1975]. Lower loadings could inhibit productivity due to reduced nutrient inputs. Higher loadings could increase productivity, increase sedimentation in the marshes and upper bay area, and thereby increase siltation of some oyster reefs in the upper bay area. The point at which increased sediment becomes detrimental is not known. If flow from the aquifer did cease under drought or even "average" conditions, a best case reduction in net freshwater inflow to the bay would be approximately 10% (assuming that municipal returns remain constant at 60%). While a 10% reduction in average net freshwater inflow would likely be stressful to the bay system, the great overall reduction in inflow water quality would likely be more significant.

The Guadalupe River is generally characterized by excellent water quality [TDWR, 1978]. However, this quality would certainly be diminished if springs issuing from the Edwards aquifer ceased to flow. The San Antonio River during low flow periods consists almost entirely of treated municipal wastewater. Because there would be a smaller overall flow in the rivers, the concentrations of pollutants from both permitted and nonpoint sources would increase. Thus, concentrations of nutrients that come from agricultural runoff, such as nitrogen and phosphorous which can lead to eutrophication when present in sufficient concentration, will increase. Concentrations of various permitted pollutants from the oil and gas facilities located around the bay area would also increase. Levels of pollutants produced from municipal wastewater treatment plants would increase. It is also likely that, with the increased oxygen demand on the rivers, the dissolved oxygen concentration entering the bay would be decreased.

Currently, about 60% of the water pumped from the Edwards aquifer for municipal use is returned after treatment to the destination streams [CH2M Hill, 1986]. This treated water is of significantly lower quality than that which flows from the Edwards aquifer. For example, the BOD of water flowing from the Edwards aquifer is approximately 1 milligram per liter (mg/L), while that permitted by the state for discharge by San Antonio wastewater treatment plants is 10 mg/L. With greater volumes of water pumped from a dwindling resource, municipalities will likely begin reuse techniques to supplement pumping, which will reduce the 60% recharge figure [CH2M Hill, 1986]. These changes and others could potentially have a great impact on the bay ecosystem.

### 4.7.2 Estimated Flow Limits

It was estimated by Childress et al. [1975] that an inflow of 1.6 to 2.4 million AF/yr to the bay system would be optimal for white shrimp production, 1.8 million AF/yr would be optimal for oyster production, and 0.6 to 2.8 million AF/yr would be optimal for crabs [Childress et al., 1975]. Childress claimed that with the current data, minimum inflow amounts could not be predicted based on commercial finfish landings [Childress et al., 1975]. An approximate minimum inflow of 1.2 million AF/yr to sustain reasonable commercial fishery production was set by Powell [1977]. A minimum gauged freshwater inflow of 750,000 AF/yr to the bay was necessary to maintain viability [CH2M Hill, 1986] and 1,620,000 AF/yr is needed to maintain the current condition of the bay. These inflows are shown in Table 4.7.

**Table 4.7** Estimated Inflow Requirements for Maximum Production of Selected Species [Childress et al., 1975; Powell, 1977; CH2M Hill, 1986]

| Estimator | For | Volume (acre-feet) |
|---|---|---|
| Childress | white shrimp* | 1.6-2.4E+06 |
| Childress | oysters* | 1.80E+06 |
| Childress | crabs* | 0.6-2.8E+06 |
| Powell | finfish* | 1.20E+06 |
| CH2M Hill | maintenance | 1.62E+06 |
| CH2M Hill | species viability | 7.50E+05 |

*for optimal production

The TWC management plan calls for reductions in ground-water pumping when the hydraulic head at an index well location falls below a predetermined trigger level. The plan calls for an eventual pumping rate of 400,000 AF per year (1989 pumping was 542,400 AF [EUWD, 1991]) and that this rate should meet the following goals: "achieve water conservation; maximize beneficial use of the water available for diversion from the underground river; protect water quality and the public health, safety, and welfare; protect aquatic and wildlife habitat; and provide for instream uses and bays and estuaries" [TWC Regulations, Chapter 298, 1992]. This pumping rate corresponds to a specific level of the index well. Considering that this flow rate is considerably less than the current average pumping rate, significant change to the inflow to the bay system would not occur on an average annual basis. However, as seasonal variations in inflow to the bays are important, an instantaneous flow standard might provide a greater margin of stability.

## 4.8 THE EDWARDS AQUIFER—AN UNDERGROUND RIVER?

Before this question can be answered, a good definition and description of a "river" are required. According to Webster's Collegiate Dictionary, a "river" is a "natural stream of water of considerable volume", whereas a stream means "any body of flowing fluid" or "an unbroken flow." Based on our experience, the following characteristics of a "river" can be defined:

(1) it has a confined riverbed,

(2) there exists a mean, overall direction of flow,

(3) the direction of flow across a cross section of the river can vary locally,

(4) the flow rate can change significantly over time,

(5) the flow in the river is driven by gravity,

(6) part of the riverbed can be filled with gravel, rocks, etc.,

(7) in periods of low flow, the stream of water can be limited to flow through this bed of rocks, and

(8) existence of biological life.

If the Edwards aquifer resembles these characteristics, it can be truly called an underground river.

As previously described, the overall direction of flow of water in the Edwards aquifer is from west to east, with some regional deviations from the main direction of flow. Water entering the aquifer has a direction of flow from north to southeast. As soon as it reaches the confined part of the aquifer, it starts to flow east. Water from the West Nueces, Nueces, Dry Frio, Frio, Sabinal, Seco, Hondo, Medina, Helotes, Salado, Cibolo, and Dry Comal basins is transported through the aquifer and mainly discharged into the Guadalupe River through San Marcos Springs and Comal Springs. During the dry season, many of those rivers can "disappear" completely into the aquifer. Hence, conditions (2) and (3) are satisfied.

Condition (1), concerning the banks of the underground river, is harder to meet. The northern boundary of the aquifer is its northern updip limit of the recharge zone. This boundary can be defined as a bank since the "updip" consists of and impermeable geologic formation (the Glen Rose Formation). The southern boundary is the so-called "bad water line." Although it is a downdip fresh water limit in the same geological formation (Georgetown Limestone, Edwards Aquifer Group), the "bad-water line" is an effective physical barrier that divides the saline and freshwater parts of the aquifer, which have totally different structures. The western and eastern lateral boundaries are groundwater divides.

The movement of water is gravity driven, and the gradient in the aquifer is about 0.42 to 0.11 m/km. In addition, the flow through the aquifer varies with time as a function of hydrological conditions, hence, conditions (4) and (5) are also satisfied.

Water in the Edwards aquifer circulates freely along fractures and faults and through honeycombed zones, channels, and caverns. Flow through these structures can be compared with flow through a bed of gravel, as is often the case in ephemeral rivers. However, the aquifer porosity is small compared to the porosity of a gravel bed. Flow rates vary from 0.6 to 9.4 m/d [Hammond, 1986; Harden, 1988], which is about 50 to 500 times larger than for most other aquifers in Texas. The average annual volume of water transported through the aquifer is about 300,000-360,000 acre-feet. This is a considerable volume.

There is a wide variety of biota present in the aquifer, more than in any other aquifer in Texas; hence, condition (8) is satisfied.

Based on the arguments above, the Edwards aquifer can be considered an underground river, independent of legal aspects or considerations. This implies, however, that the "firm yield" needs to be calculated accordingly. Also, the residence time of water in the aquifer is rather long for a river. Thus, the Edwards aquifer is neither a typical river nor a typical aquifer. Hence, managing the Edwards aquifer will be a unique task.

Readers interested in legal arguments about whether the Edwards aquifer is an underground river are referred to "The Edwards Aquifer: Underground River of Texas" [GBRA, 1988].

## 4.9 CONCLUSIONS

Whether one is concerned about the effects of reduced streamflow on wildlife or not, one must decide what the priorities of the community are. Do we want to preserve the whole ecosystem like it is, or is a different ecosystem, adapted to less water, of the same value? The options are legally limited because, according to the Endangered Species Act, the habitat of an endangered species should be kept undisturbed. The specific minimum springflow needed for the endangered species to exist in the springs and streams is not known, but a long cessation of springflow will jeopardize the endangered species. The choice to manage the aquifer under the original TWC plan will likely lead in the future to "dry" springs, and thus eradication of the endangered, as well as other, species. However, dry springs may be a natural condition as well.

One likely consequence of the TWC plan is the construction of reservoirs upstream from the bay system. These reservoirs would alter the sediment and nutrient loadings entering the bay system; they may also have a minimal effect on the overall quality of the water entering the bay [CH2M Hill, 1986]. Likewise, reservoirs might be used to ensure proper flow to the bay system when needed on a seasonal basis for the development of bay life.

It is not likely that the TWC goals for springflows can be met when the proposed reductions are implemented. The plan requires a flow of "100 cfs at Comal Springs at least 80% of the time, except during severe droughts." For ecosystems in the springs, rivers, and estuaries, drought periods are the most critical conditions. It is important to have guaranteed daily flow levels, not annual flow levels, for these systems. In order to effectively protect the Edwards aquifer and its downstream environment, pumpage probably needs to be limited to 200,000 AF/yr. This fact is recognized by the TWC but its implementation is not considered feasible. Since limiting the pumpage to this level is considered to be unrealistic, even after conservation measures are taken, the only option is the use of alternative water resources. If possible, this should be incorporated in the management plan.

Finally, the Edwards aquifer is neither a typical river nor a typical aquifer, though it probably resembles an underground river more closely than an aquifer.

# 5.0 HYDROLOGIC MODELING AND SIMULATION

Chrysi S. Laspidou, J. Francisco Oliveras-Cardenas,
Andrew E. Schulman, David W. Watkins, Jr., and Daene C. McKinney

## 5.1 INTRODUCTION

The TWC management plan for the Edwards aquifer states that the measures in the plan "would have maintained a 100 cfs springflow at Comal Springs at least 80% of the time as determined by hydrologic modeling using the Texas Water Commission's Management Evaluation Model for the Edwards Aquifer" [TWC, 1992]. Thus, in evaluating the plan, it is important also to evaluate the hydrologic modeling effort. In this section, the models used by the TWC will be evaluated and compared to other available models. Though only one other regional modeling effort has been identified—by the U.S. Geological Survey—a comparison of these two modeling efforts can yield some insights. The evaluation of the model used by the TWC will entail the following: (1) a comparison of measured and simulated springflows, (2) a sensitivity analysis with respect to aquifer stresses, and (3) an analysis of the proposed management plan using the model.

## 5.2 REVIEW AND COMPARISON OF EXISTING MODELS

At least three government agencies have developed models of the Edwards aquifer—the TWC, the TWDB, and the USGS. Also, there is some modeling work being done at the EARDC, and there are various reports which comment on the accuracy and reliability of the current models.

### 5.2.1 The TWC's Management Evaluation Model

This model, reportedly used by the TWC in developing the management plan, is very simple. It is a finite-difference model containing one layer, 6 rows, and 33 columns. Each grid cell is about 25 square miles in size. This model was calibrated and verified using data from 1959-1989, which does not include the drought of record [Peters and Crouch, 1991]. Spring flow was not simulated in the model, and few details on calibration and verification were given. Over time, the model does match the average head in well J-17 (a well whose level correlates very closely to springflow at Comal Springs), but there is no mention of the simulated or measured head level variance. Also, the model was calibrated for steady-state conditions approximated by averaging recharge, pumpage, and springflow for the years 1934-1988. Most likely, steady-state conditions occurred only before the 1930s.

Though it might seem that the TWC has based its original management plan on a very technically unsound model, it turns out that the TWC has also relied on a model developed by the TWDB for the evaluation of the plan. This model is much more complex and technically sound, as will be discussed in the next section.

### 5.2.2 Modeling by the TWDB

The "refined" groundwater model currently used by the TWDB [Thorkildson and McElhaney, 1992] is a more recent version of the original TWDB model [Klemt et al., 1979]. Both TWDB models are based on the program of Prickett and Lonnquist [1971]. Modifications to the Prickett and Lonnquist program were made by the TWDB (formerly the Texas Department of Water Resources) and documented in the model *GWSIM* [TDWR, 1974]. The refined TWDB is called *GWSIM-IV* [Paul McElhaney, TWDB, personal communication, 1992].

The aquifer parameter and recharge values used in the refined TWDB model were primarily obtained from the original model [Klemt et al., 1979]. The original model used annual time steps and a single-layer, 80x31-cell finite-difference grid, in which cell sizes ranged from 1.2 square miles to 18.5 square miles (Figure 5.1). The grid was oriented in a southwest to northeast manner in order to better match the direction of flow. All boundary conditions were no-flow conditions, and homogeneous, isotropic conditions were assumed in each cell [Klemt et al., 1979].

The results of the original TWDB model calibration were considered acceptable by Klemt et al. [1979]. Using data from 1947-1959, annual mean error (as represented by the difference in simulated heads and measured heads) ranged from 0.68 to 6.81 feet. About 75% of the simulation errors were within 25 feet of observed values. Mean springflow error was 4.3%, though in some years the absolute error was much greater [Klemt et al., 1979]. Klemt et al. [1979] ran a number of future simulations and made the following recommendations, most of which remain true today:

(1) Yearly time steps are probably not adequate for springflow simulation, since the springs may be dry only a part of the year. Thus, more research is needed to determine monthly pumpage and recharge values.

(2) More research is needed to determine the validity of assuming that the "bad water line" (to the south) can be treated as an impermeable boundary.

(3) More research is needed to determine the boundary locations of the Edwards aquifer and whether or not flow from other formations is significant.

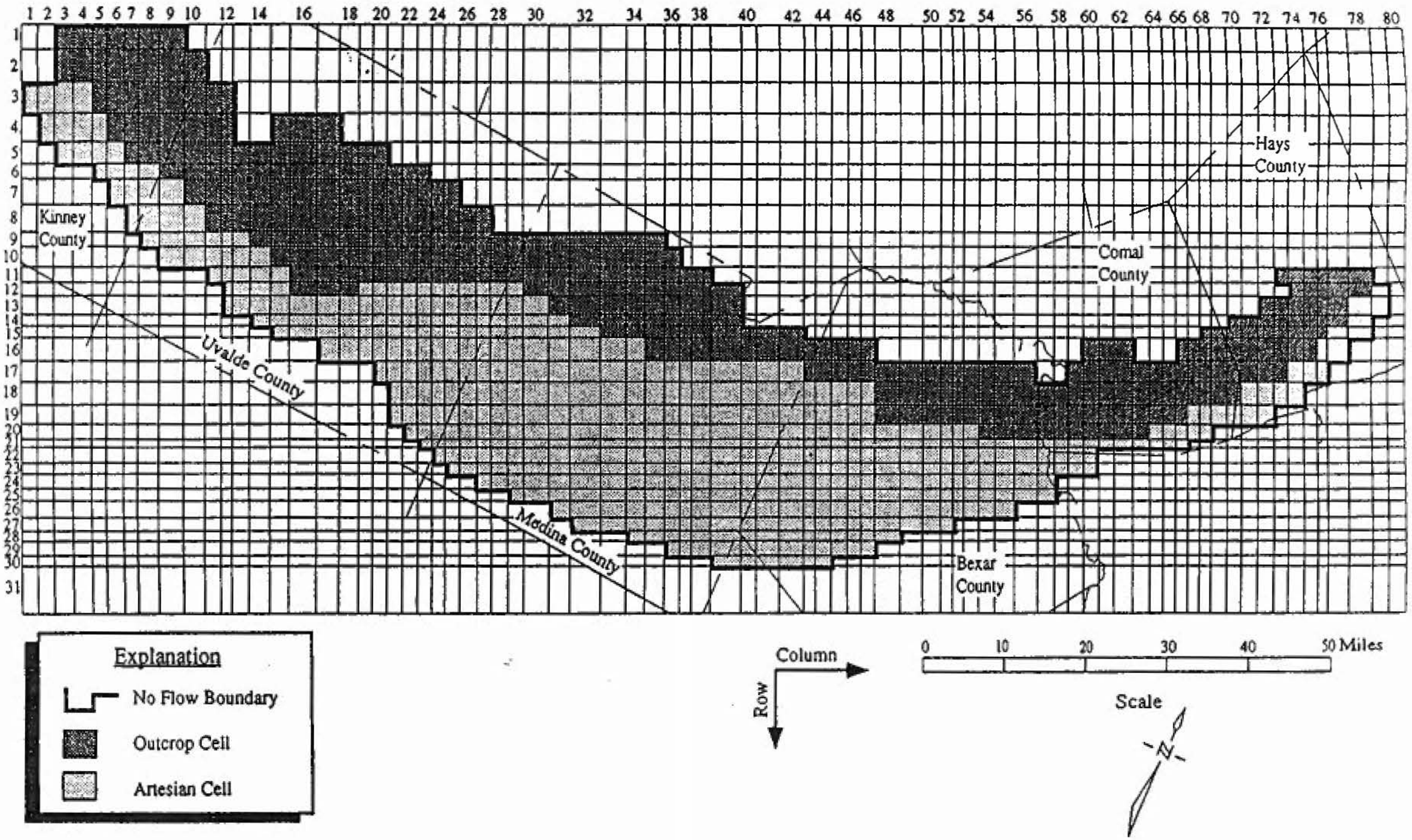



**Figure 5.1** Finite-Difference Grid for the Edwards Aquifer [Thorkildson and McElhaney, 1992]

For the most part, Thorkildson and McElhaney [1992] followed these recommendations in developing the refined TWDB model. Monthly time steps were used, and research was done to determine the yearly distribution of recharge and pumpage. The spatial distribution of pumpage was kept the same as in the original model. Recharge distribution was also kept the same, except for increased recharge at the cell representing San Marcos Springs. This was done in order to better represent the local flow component from the outcrop area, as suggested by Puente [1976].

Other modifications involved analyzing new aquifer data and incorporating some of the parameters estimated by the USGS [Maclay and Land, 1988] into the refined model. However, flow from other formations was neglected, and the local flow component at the San Marcos Springs was not fully simulated. Also, as in all regional models, Thorkildson and McElhaney point out that water levels represent regional levels and not water levels in individual wells, although these can be estimated accurately using analytical well models. This should be an important consideration when simulating springflows, which are quite local in nature.

### 5.2.3 Modeling Efforts at the USGS

Maclay and Land [1988] developed a finite-difference model (monthly time steps, 1 layer, 40 rows, and 72 columns) to refine the storage and flow concepts of the Edwards aquifer. The model was calibrated only with measured data for the period 1972-1976, but it was shown to predict springflows during this time adequately, as shown in Figure 5.2. The phase error seen in the period 1974-1976 was accredited to the use of annual average recharge rather than monthly recharge.

Though the structure of this model was not much different than the original TWDB model, it was used for a different purpose—to better understand the physical system rather than just to predict its response. With this goal in mind, Maclay and Land [1988] concluded that (1) significant cross-formational flow probably exists at a number of locations, (2) the total quantity of water available from storage should include parts of other formations, and (3) subsurface springs discharge along faults, and flows across faults are significant in several locations. Also, several barrier faults redirect flow in a few locations.

Work is currently under way at the USGS to incorporate these findings into modeling studies at two different scales: (1) a regional aquifer systems analysis (RASA) of the south-central Texas region and (2) a subregional model of the Edwards aquifer and

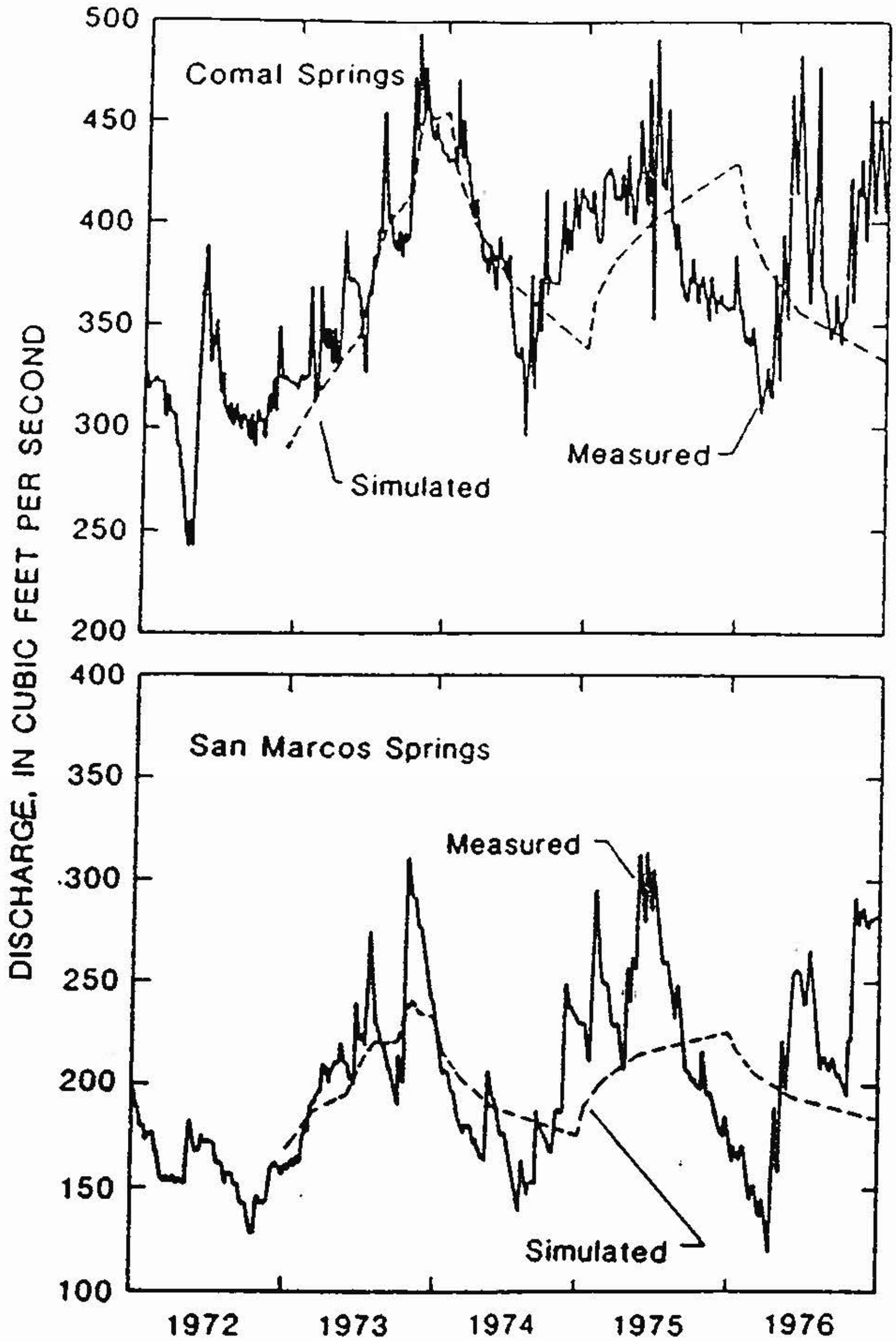



**Figure 5.2** Comparison of Simulated and Measured Springflow [Maclay and Land, 1988].

adjoining formations. The RASA will cover 55,600 square miles and will use a steady-state simulation model because of the uncertainty involved in pumping rates in many rural areas. The subregional model will be a two-layer finite-element model, with 14,000 elements about 0.5 to 1.5 square miles in size. This model will attempt to incorporate all of the hydrologic conditions affecting the Edwards aquifer, including cross-formational flow and flow across the "bad-water" line. A schematic of the conceptual model is shown in Figure 5.3 [Eve Kuniansky, USGS, personal communication, 1992].

The USGS subregional model could be a significant improvement over the refined TWDB model for the following reasons: (1) it has finer discretization than the TWDB model; (2) it uses two layers rather than one, (3) it allows for anisotropy, and (4) it simulates flow components not previously considered. Also, the finite-element method offers some advantages over the finite-difference method, including: (1) a more variably spaced mesh is possible; (2) the direction of anisotropy can be varied; and (3) irregular geometry is better fit. The primary disadvantage of finite-element modeling is that it is harder to prepare the model input data. This is because node and element numbering does not follow a uniform, rectangular grid, yet knowing which nodes are associated with which elements is essential. However, a graphical method using a geographic information system has been developed to simplify this task [E. Kuniansky, USGS, personal communication, 1992].

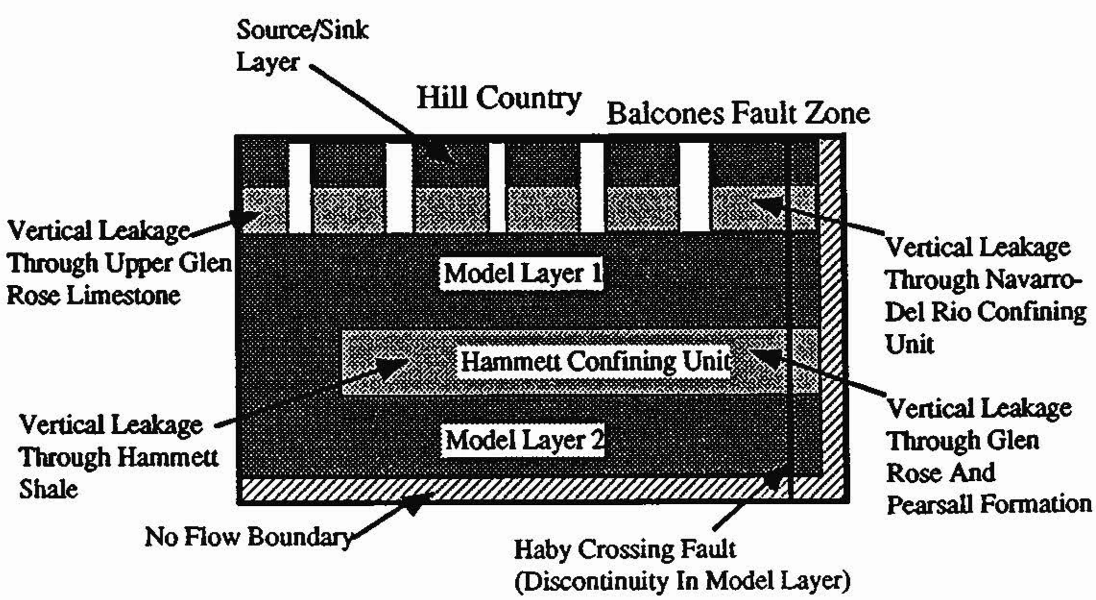



**Figure 5.3** USGS Subregional Model Conceptualization

### 5.2.4 Other Modeling Efforts

Work is being done at the EADRC to develop a lumped-parameter model for the Edwards aquifer. This model divides the aquifer into five "pools" in which a volumetric budget is maintained. The model also differs from current models in that recharge is not "assigned," but is instead calculated from streamflow data. Thus, it is hoped that smaller time increments can be used [N. Wanakule, EADRC, personal communication, 1992].

## 5.3 HYDRAULIC SIMULATION

Before reviewing the refined TWDB model in more detail, a brief overview of the method used will be given. The differential equation for a non-steady flow in a heterogeneous, anisotropic aquifer is [Bear, 1972]:

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W$$

where:

| | | |
|---|---|---|
| $T$ | = | transmissivity [$L^2/T$] |
| $S$ | = | storativity [dimensionless] |
| $h$ | = | hydraulic head [L] |
| $W$ | = | net groundwater outflow per unit area [L/T] |
| $t$ | = | time [T] |
| $x, y$ | = | rectangular coordinates |

In order to find a numerical solution for this equation, the following steps are taken:

(1) Replace the continuous aquifer by a set of discrete elements (finite difference grid). Each discrete element is a cell and the center of the cell is a node. Each cell is referenced by its row and column numbers.

(2) Write the equation in a finite difference form for each of the cells. For cell (i,j) the equation is:

$$\frac{1}{\Delta x_j}\left[\left(T_{i,j+\frac{1}{2}} \frac{h_{i,j+1} - h_{i,j}}{\Delta x_{j+\frac{1}{2}}}\right) - \left(T_{i,j-\frac{1}{2}} \frac{h_{i,j} - h_{i,j-1}}{\Delta x_{j-\frac{1}{2}}}\right)\right] +$$

$$\frac{1}{\Delta y_i}\left[\left(T_{i+\frac{1}{2},j} \frac{h_{i+1,j} - h_{i,j}}{\Delta y_{i+\frac{1}{2}}}\right) - \left(T_{i-\frac{1}{2},j} \frac{h_{i,j} - h_{i-1,j}}{\Delta y_{i-\frac{1}{2}}}\right)\right] =$$

$$\frac{S_{i,j}}{\Delta t}\left(h_{i,j} - H_{i,j}\right) + W_{i,j}$$

where:

$\Delta x_j$ = grid spacing in the $x$ direction for column $j$

| | | |
|---|---|---|
| $\Delta x_{j+1/2}$ | = | distance between node $i,j$ and node $i,j+1$ |
| $\Delta y_i$ | = | grid spacing in the $y$ direction for row $i$ |
| $\Delta t$ | = | time step |
| $T_{i,j+1/2}$ | = | transmissivity between node $i,j$ and $i,j+1$ |
| $S_{i,j}$ | = | storage coefficient for cell $i,j$ |
| $h_{i,j}$ | = | head at node $i,j$ at end of time step |
| $H_{i,j}$ | = | head at node $i,j$ at beginning of time step |
| $W_{i,j}$ | = | net withdrawal per unit surface area for cell $i,j$ |

Rearranging terms and multiplying by the area of cell i,j, we can write

$$A_{i,j}(h_{i,j-1}-h_{i,j})+B_{i,j}(h_{i,j+1}-h_{i,j})+C_{i,j}(h_{i-1,j}-h_{i,j})+D_{i,j}(h_{i+1,j}-h_{i,j})$$
$$=E_{i,j}(h_{i,j}-H_{i,j})+Q_{i,j}$$

where:

$$A_{i,j}=\frac{b_{i,j}\Delta x_{j-1}+b_{i,j-1}\Delta x_j}{\Delta x_{j-1}+\Delta x_j}K^x_{i,j-1}\Delta y_i\frac{2}{\Delta x_{j-1}+\Delta x_j}$$

$$B_{i,j}=\frac{b_{i,j+1}\Delta x_j+b_{i,j}\Delta x_{j+1}}{\Delta x_j+\Delta x_{j+1}}K^x_{i,j}\Delta y_i\frac{2}{\Delta x_j+\Delta x_{j+1}}$$

$$C_{i,j}=\frac{b_{i,j}\Delta y_{i-1}+b_{i-1,j}\Delta y_i}{\Delta y_{i-1}+\Delta y_i}K^y_{i-1,j}\Delta x_j\frac{2}{\Delta y_{i-1}+\Delta y_i}$$

$$D_{i,j}=\frac{b_{i+1,j}\Delta y_i+b_{i,j}\Delta y_{i+1}}{\Delta y_i+\Delta y_{i+1}}K^y_{i,j}\Delta x_j\frac{2}{\Delta y_i+\Delta y_{i+1}}$$

$$E_{i,j}=\frac{S_{i,j}\Delta x_j\Delta y_i}{\Delta t}$$

$$Q_{i,j}=W_{i,j}\Delta x_j\Delta y_i+\delta R_{i,j}(h_{i,j}-RD_{i,j})$$

| | | |
|---|---|---|
| $b_{i,j}$ | = | saturated thickness of cell $i,j$ [L] |
| $K^x_{ij}$ | = | hydraulic conductivity between cells $i,j$ and $i,j+1$ [L/T] |
| $K^y_{ij}$ | = | hydraulic conductivity between cells $i,j$ and $i+1,j$ [L/T] |
| $R_{i,j}$ | = | change in flow rate per unit change in actual head |
| $RD_{i,j}$ | = | reference head |
| $\delta$ | = | 1 for river cells, cells with leakage out of the aquifer, and spring cells with $H_{i,j}>RD_{i,j}$; 0 otherwise. |

The saturated thickness is equal to the total thickness for confined aquifers and to the difference between the hydraulic head and the bottom level for unconfined aquifers. The term $Q_{i,j}$ considers pumping and injection wells in the first part of the term. In the second part, the net outflow to rivers and springs and the leakage through the border cells are estimated. The evaluation of $R_{i,j}$ takes into account the process being modeled. A satisfactory way to model this is to assume that the aquifer is separated from the water source or sink by a confining bed. In such a case we can write:

$$R_{i,j} = \left( \frac{K' A_c}{b'} \right)_{i,j}$$

where:

| | | |
|---|---|---|
| $K'$ | = | hydraulic conductivity of the confining bed [L/T] |
| $A_C$ | = | area of the confining bed through which leakage takes place [$L^2$] |
| $b'$ | = | thickness of the confining bed [L] |

Note that the spring cells have the additional requirement of having a water head greater than the reference head, which is the level of the lower point of the spring outlet.

(3) Solve numerically the resulting set of linear equations.

The finite difference equation is written for each unknown in the finite difference grid resulting in an system of equations with one unknown for each node in the mesh. This system of equations is solved by the iterative alternating direction implicit (IADI) method. With this method, the equations are written and solved sequentially, first for the columns and then for the rows, assuming that the solution of the columns is known.

## 5.4 COMPARISON OF MEASURED AND SIMULATED VALUES

The evaluation of the accuracy of the refined TWDB model in predicting flow conditions at the springs was done by comparing the measured flows and simulated values obtained by the TWDB at the two major springs: Comal and San Marcos. The model was run for the period of 1978-87, and the only variable that was considered for comparison was springflow. Other predictive variables, such as aquifer storage volume or well J-17 water level, were not evaluated due to time limitations; however, it is apparent that more work is needed to simulate local flow components. (In contrast to regional flow components, local flows consist of water which enters and leaves the aquifer at adjacent topographical highs and lows.)

The measured and simulated flows using TWDB data sets [Paul McElhaney, TWDB, personal communication, 1992] for the 1978-87 period for Comal and San

Marcos Springs are shown in Figures 5.4 and 5.5, respectively. From the graph in Figure 5.4, one can see that under the mild drought conditions of 1984, the refined TWDB model predicts flow at Comal Springs quite well. The mean and standard deviations for the measured values (in AF/month) are 17,081 and 4,863, respectively, while the corresponding simulated values are 17,839 and 4,798, respectively. The correlation coefficient is relatively high: .898. These statistical results are summarized in Table 5.1.

As shown in Figure 5.5, the refined model does not predict San Marcos Springs flow as well. The predicted values are approximately 30% lower than the measured values. This discrepancy can probably be attributed to the fact that flow at San Marcos springs comes partially from local discharge. In an attempt to account for this local flow, a fraction of the recharge to the basin was moved directly to the cell containing the springs; however, this local flow component still was not fully simulated [Thorkildson and McElhaney, 1992]. This result shows the need for a subregional model. A statistical analysis of the measured and simulated data similar to the one described for Comal Springs was done. The results are summarized in Table 5.2.

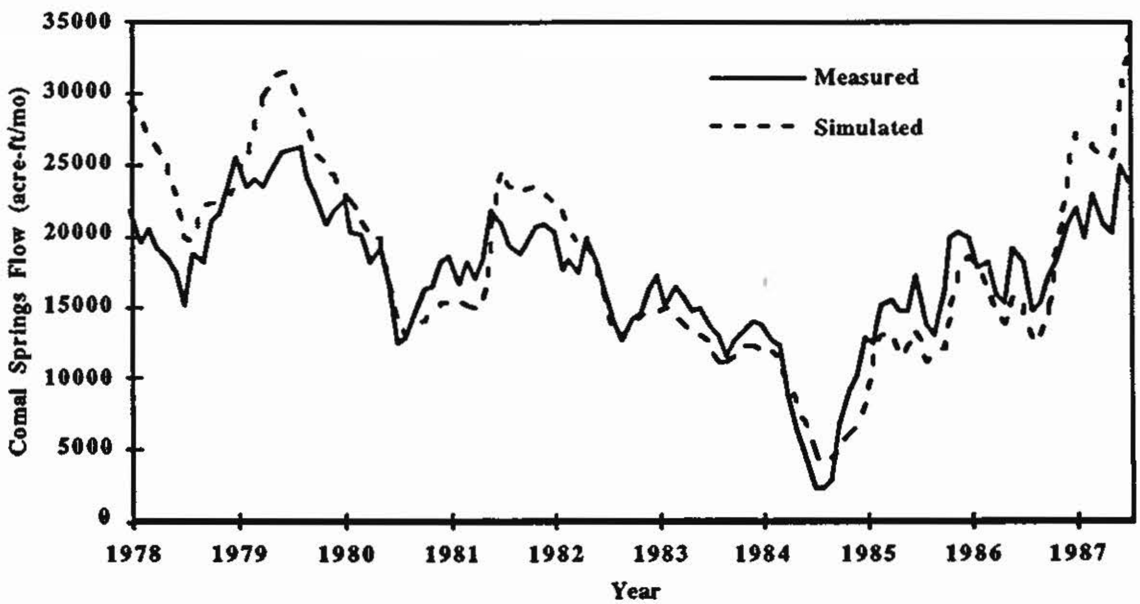



**Figure 5.4** Measured and Simulated Comal Springs Flow for 1978-87

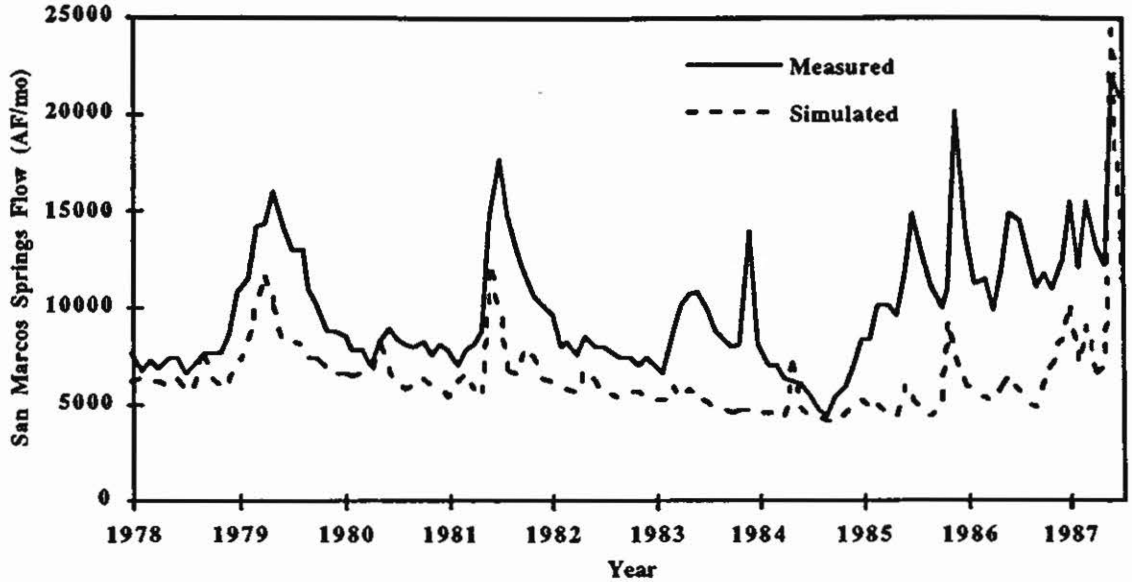



**Figure 5.5** Measured and Simulated San Marcos Springs Flow for 1978-87

**Table 5.1** Comal Springs Statistical Analysis Results for 1978-87

| | Measured (AF/month) | Simulated (AF/month) |
|---|---|---|
| Mean | 17,081 | 17,839 |
| S.D. | 4,863 | 4,798 |
| Correlation | 0.898 | |

**Table 5.2** San Marcos Springs Statistical Analysis Results for 1978-87

| | Measured (AF/month) | Simulated (AF/month) |
|---|---|---|
| Mean | 9,813 | 6,340 |
| S.D. | 3,326 | 2,355 |
| Correlation | 0.648 | |

## 5.5 SENSITIVITY ANALYSIS

A sensitivity analysis is the evaluation of the change in a predicted variable due to the modification of a certain model parameter, provided that the other parameters remain constant. In this study, the change in the average flow in Comal and San Marcos Springs due to variations in the pumpage or recharge rate was analyzed.

The basic information with regard to the pumpage and recharge was obtained from the TWDB [Klemt et al., 1979; Thorkildson and McElhaney, 1992]. The data correspond to the period ranging from 1978 to 1987 when the average annual pumpage was 450,000 AF/yr and the average annual recharge was 410,000 AF/yr. In our analysis, the pumpage and recharge were changed within a range of -20% to +20% for each parameter. This means the maximum variations simulated were 90,000 AF/yr less/greater pumpage and 82,000 AF/year less/greater recharge. After nine simulations in which the sensitivity of the average springflow at Comal and San Marcos was computed, the following equations were determined by linear regression ($r^2 = 0.99$):

$$FLOW_{Comal} = 17733 + 16582 * RA - 17901 * PA$$

$$FLOW_{SanMarcos} = 6337 + 3712 * RA - 1609 * PA$$

where $FLOW_{Comal}$ and $FLOW_{San\ Marcos}$ are the average springflows (AF/month) for the period considered, $PA$ is the pumpage adjustment, and $RA$ is the recharge adjustment. For instance, setting $PA$ to 0.1 represents a 10% increase in pumping; setting it to -0.1 represents a 10% decrease. It should be noted that the equations indicated above are valid only for values of the adjustments within the range of -20% to +20% and for flow conditions representative of 1978-1987. For higher adjustments the equations are not necessarily valid. According to these equations, and for the pumpage and recharge rates from 1979-1987, the average flows at Comal and San Marcos Springs were 52% and 19% of the recharge, respectively. During that period, the pumpage was 110% of the recharge. In other words, for every 100 AF of recharge, there was 52 AF of flow at Comal Springs, 19 AF at San Marcos Springs, and 110 AF of pumping in the aquifer. Thus, neglecting other discharges, 181 AF was discharged for each 100 AF of recharge.

Two different approaches can be used to interpret these results. First, we can consider how much the springflows change due to an error in the pumpage or recharge input data. Second, we can consider how much the springflows change due to a new policy for pumpage or recharge (i.e., artificial recharge). With regard to the first approach, we can conclude that:

(1) Errors in the pumpage or recharge input data generate errors of nearly the same percentage for the Comal Springs flow. That is, an error of ±10% in the pumpage rate will decrease (increase) the flow at Comal Springs by 10.1%, and an error of ±10% in the recharge rate will increase (decrease) the flow by 9.4%.

(2) Errors in the pumpage or recharge input data generate smaller errors for the San Marcos Springs flow. That is, an error of ±10% in the pumpage rate will decrease (increase) the flow at San Marcos Springs by 2.5%, and an error of ±10% in the recharge rate will increase (decrease) the flow by 5.9%.

It can be noted that San Marcos Springs flow is not as sensitive to errors in the input data as is Comal Springs flow. Since San Marcos Springs is at a lower elevation, it is not so sensitive to changes in aquifer storage. With regard to the second approach, we can conclude that:

(1) If pumpage is not changed, an increase (or decrease) in the recharge of 1000 AF/yr will lead to an increase (or decrease) at Comal Springs of 485 AF/yr (40.4 AF/month) and at San Marcos Springs of 109 AF/yr (9.1 AF/month). This means that only 59% of the increase (or decrease) in the recharge will flow to the two springs considered.

(2) If recharge is not changed, a decrease (or increase) in the pumpage of 1000 AF/yr will lead to an increase (or decrease) at Comal Springs of 477 AF/yr (40.0 AF/month) and at San Marcos Springs of 43 AF/yr (3.6 AF/month). This means that only 52% of the decrease (or increase) in the pumpage will affect the two springs considered.

Since a decrease in the pumpage rate (or increase in the recharge) does not produce an increment in the springflows of the same amount of water, it should be noted that the other part of the water is flowing to other minor springs or remaining in the aquifer and raising the water level. With respect to maintaining minimum springflows of 100 cfs, and not accounting for any time lags (the time required for the springflows to respond to pumpage reductions), we can conclude:

(1) If the aquifer level is such that Comal Springs *has just gone dry*, and the net storage increase of the aquifer would otherwise be zero, restoring a flow of 100 cfs (72,396 AF/yr) would require pumpage reductions of 152,000 AF/yr. If the aquifer level is such that San Marcos Springs *has just gone dry*, and the net storage increase of the aquifer would otherwise be zero, restoring a flow of 100 cfs would require pumpage reductions of 1,684,000 AF/yr, which is far greater than the average annual pumpage.

(2) The assumption that the net storage increase of the aquifer is otherwise zero would probably not be true, because average annual pumpage now exceeds annual average recharge. Also, a factor of safety may be required to account for the time lag involved—to ensure protection of the endangered species, one should anticipate lower than average recharge during the time lag. Thus, even greater pumpage reductions may be needed.

## 5.6 ANALYSIS OF THE TWC MANAGEMENT PLAN

In order to evaluate the TWC management plan, the refined TWDB model was run for a hypothetical "worst case" scenario with and without the management plan. The objective was to see if the interim TWC management plan is adequate in providing significant protection to the springflows at the proposed 100 cfs level [TWC, 1992].

The scenario simulates the case that a drought similar to the one that happened in the years 1447-1956 will begin in 1993. Therefore, the 1947-59 recharge data [Thorkildson and McElhaney, 1992] with projected 1993 pumpage data were used. The projected pumpage data were obtained by scaling the 1947-1959 data up by a factor of 3.22 to give a total of 538,000 AF/year. Thus, the distribution of pumpage was the same as for the 1950's, which is probably not a good assumption, but a new data set was not required. A similar scenario was run by the TWDB, except that they used a sixty-year historical recharge record (1934-90).

The results (with and without the plan in effect) are shown in Figures 5.6 through 5.8. Specifically, in Figure 5.6 the springflow for Comal Springs is shown. Obviously, the interim plan does not provide the necessary protection for the flow in Comal Springs because it runs dry for almost seven years. In other words, if a severe drought occurs this year, the interim plan does not guarantee that the springs will still maintain a flow. Note that this conclusion will not be altered even after allowing for the errors found in performing the sensitivity analysis and comparing measured and simulated values.

The plan protects the San Marcos Springs much better, though the 100 cfs (6033 AF/mo) level is still not maintained for the entire period. As shown in Figure 5.7, with the management plan, the flow never goes to zero; without the management plan, flow does go to zero for approximately five years. The interim plan in this case may be adequate in providing protection of the springflow, especially since the simulated values are 30% lower than the measured values (i.e., local flow components are not fully simulated).

As seen in Figure 5.8, the mandatory pumpage curtailment of the management plan is in effect nearly the entire period. In this figure, a curtailment factor of 0.6 means that pumping is reduced by 40% as specified by the interim plan. Since this is the maximum curtailment called for by the plan, and springflows continue to drop even with this curtailment in effect, the plan should perhaps include greater reductions during a repeat of the drought of record.

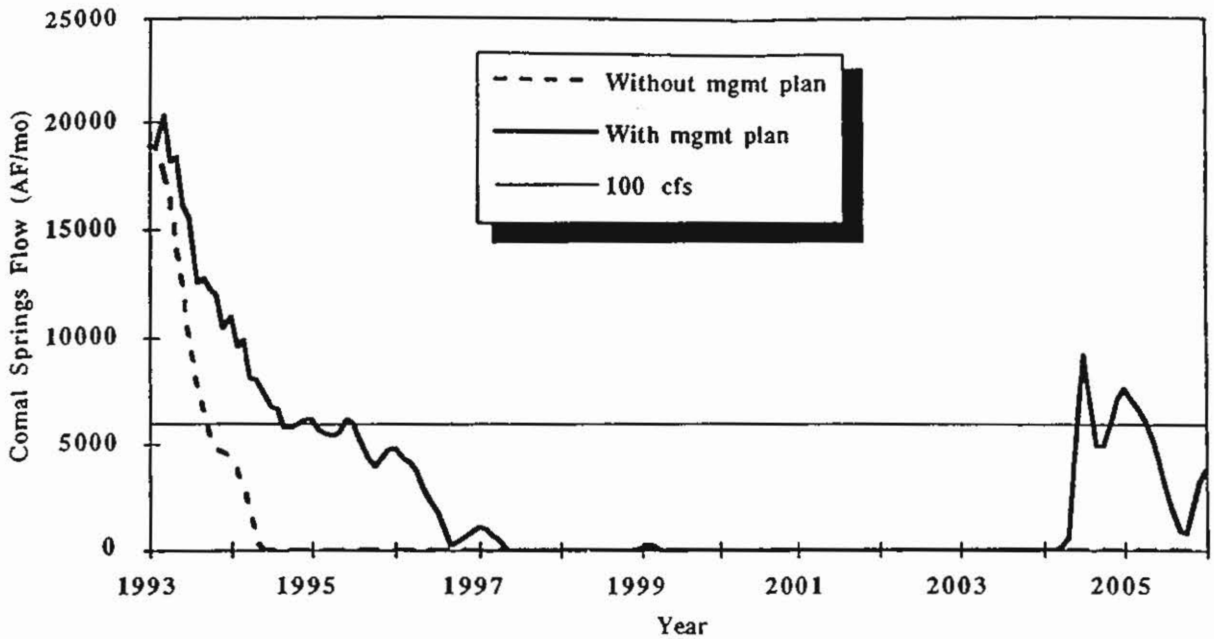



**Figure 5.6.** Simulated Comal Spring Flows (1950's recharge, 1990's pumpage).

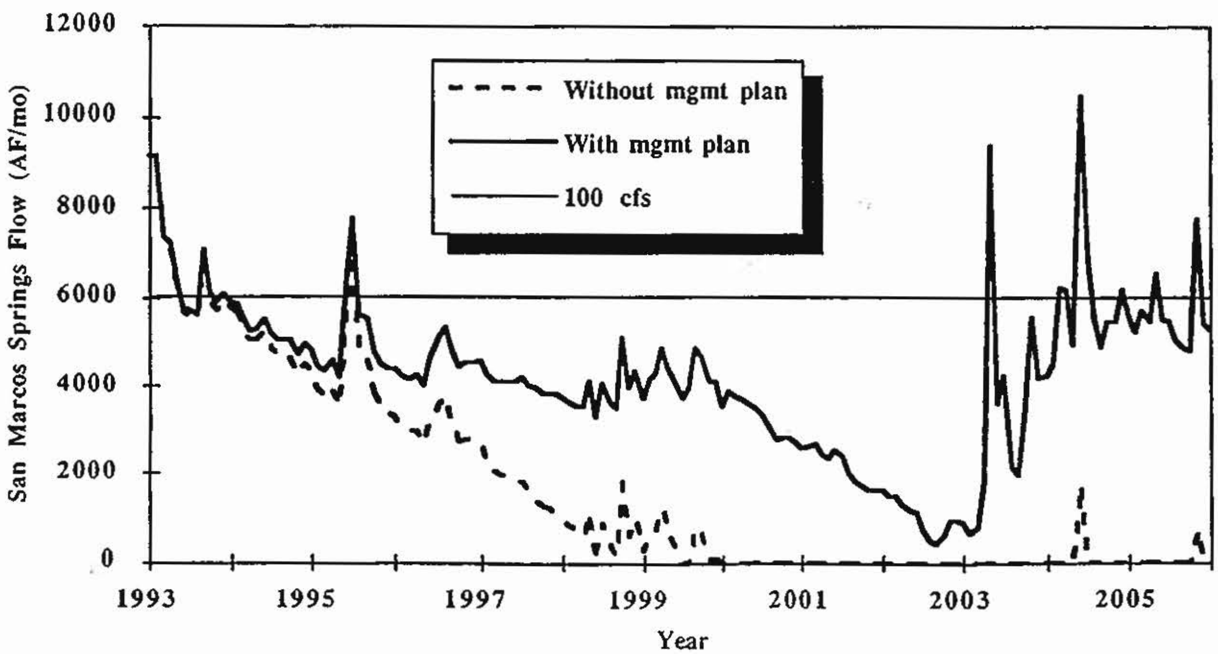



**Figure 5.7.** Simulated San Marcos Spring Flows (1950's recharge, 1990's pumpage).

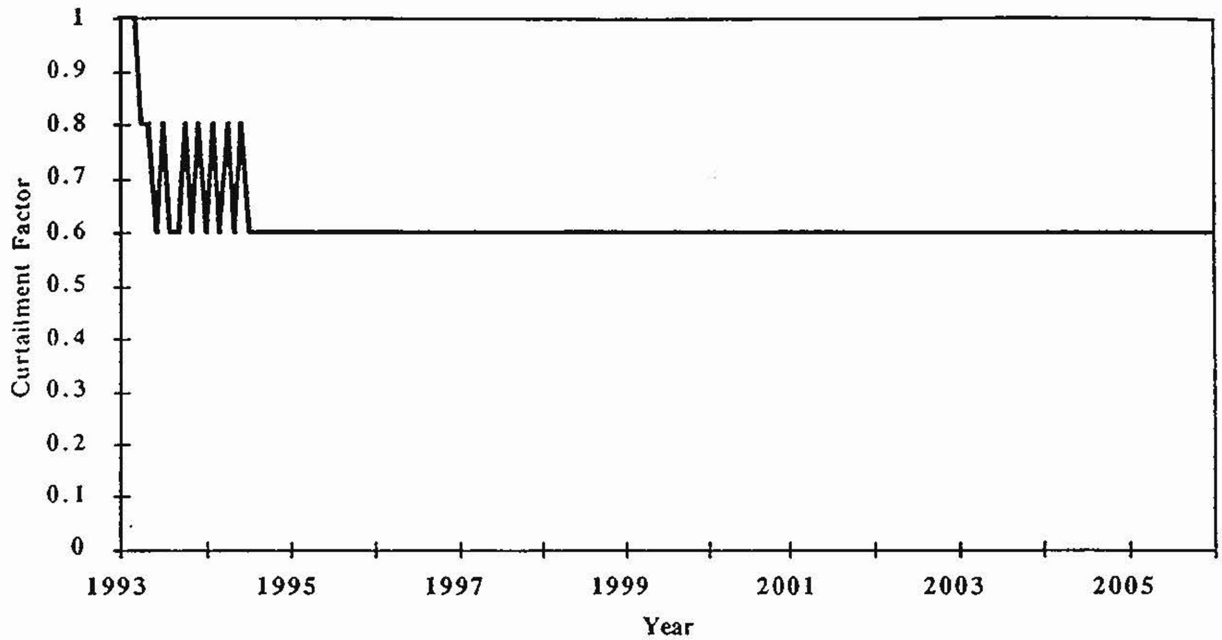



**Figure 5.8.** Pumpage Curtailment Factor (1950's recharge, 1990's pumpage)

## 5.7 CONCLUSIONS

Accurate hydrologic modeling and simulation of the Edwards aquifer is a difficult task. However, if the aquifer is to be managed efficiently, an accurate and reliable model is an essential tool. Upon evaluating the TWDB model (used by the TWC) and comparing this model to others (both existing models and those under development), the following conclusions and recommendations can be made with respect to the proposed management plan:

(1) In the TWDB model, simulated flow at San Marcos Springs is about 30% too low due to modeling error. More work must be done to simulate local flow components adequately.

(2) Simulated flow at Comal Springs is modeled more accurately, but it is more sensitive than flow at San Marcos Springs due to uncertainty in pumpage and recharge estimates. In either case, we cannot expect the accuracy of simulated springflows to be better than the accuracy of the pumpage and recharge estimates.

(3) There is less than a one-to-one correspondence between pumpage reductions and springflow increases. Thus, to increase flow at San Marcos and Comal Springs by a specified amount, pumping must be reduced by an even greater amount.

(4) Several different models of the Edwards aquifer have been developed or are being developed. The Edwards aquifer management efforts should rely on the model which incorporates the most recent research and produces the most accurate and reliable results.

(5) Based on the TWDB model, the proposed interim management plan does not come close to providing for adequate flow as specified by the TWC management plan (100 cfs) at Comal Springs during a repeat of the drought of record. The springs will likely go dry for extended periods during the next severe drought and probably even during a mild drought.

# 6.0 CONCLUSIONS

The Edwards aquifer is an incredibly valuable resource for Central Texas, and a regional management plan may be the only way to protect it. The Texas Water Commission's proposed interim management plan, calling for incentives to conserve and for mandatory pumping curtailment in time of drought, was definitely a step in the right direction. However, due to the disagreement of the affected parties, it is unlikely that this plan will ever be implemented. At this time, it appears that action by the State Legislature is needed.

Even if this plan is implemented, though, it may not protect the endangered species which rely on springflow from the aquifer. Many species require the maintenance of minimum daily flows for survival, while the proposed plan may allow the springs to go dry for extended periods of time during a drought. The plan simply will not reduce pumping enough, and in light of the projected population growth in the area, it may not even be possible to do so. Thus, a regional management plan should address the development of alternative water supplies. Also, for maximum efficiency, the plan should call for market-based schemes, such as water rights trading, to limit pumping from the Edwards aquifer.

The TWC should be aware of the limitations of the hydrologic models upon which the plan is based. Numerical simulation models are mere approximations of the real world, and decision-makers should use their results with extreme caution. A constant effort should be made to improve these models and to make them as accurate and reliable as possible.

This study has resulted in the following conclusions and recommendations:

## 6.1 LEGAL ASPECTS

The only means of protecting the Edwards aquifer is to implement a management plan. Unfortunately, all parties are not in agreement on a plan and mediation has resulted in little or no compromise. Thus, a plan cannot be implemented without some legal action. To prevent federally mandated pumping restrictions, the Legislature of the State of Texas must pass bills providing clear authority to the TWC, the EUWD, or some new authority to manage the Edwards aquifer. Until all parties can agree or the Legislature acts, the State becomes further at risk of losing many benefits from this extraordinary resource.

## 6.2 ECONOMIC AND DEVELOPMENT ASPECTS

The TWC plan for the Edwards aquifer calls for across-the-board reductions in water use by all economic sectors should a water shortage occur. Though this might seem the fairest way of implementing the plan, it does not appear to be the most economically efficient way. Reduction in irrigation water use should be the first area targeted. Reduction in municipal water use mainly through conservation should be considered as the next step in the plan. Businesses which are not water intensive, especially those in the retail and trade industries, should be targeted next since they would not be greatly impacted by water restrictions. Manufacturing industries should be targeted for water restrictions only as a last resort. Raising the price of water, thus giving it a greater economic value, during times of drought would economically encourage conservation and reduced water use. Thus, water would be allocated to its most economically beneficial use, and the economic impact of water reduction would be minimized. A water conservation method offering immediate benefits at low costs is the use of reclaimed water in municipal and industrial irrigation. Artificial recharge would be the second most viable alternative. Economic incentive rather than government mandate is the most efficient way to reduce water demand. The shift to a market-based water rights system would allow the price of water to reflect the true cost of this scarce resource. A higher price on water will stimulate conservation, development of water-saving technology, and utilization of alternative water supplies.

## 6.3 ENVIRONMENTAL ASPECTS

The effects of reduced streamflow on wildlife may dictate the priorities of water use from the Edwards aquifer. Should we preserve the whole ecosystem as it is, or is a different ecosystem, adapted to less water, of the same value? These options are limited due to the Endangered Species Act that states that the habitat of endangered species should be kept undisturbed. The minimum springflow needed for the endangered species to exist in the springs and streams is not known, but a long cessation of springflow will jeopardize the endangered species. The original TWC management plan will likely lead to dry springs and eradication of the endangered, as well as other, species.

The TWC management plan calls for reductions in pumping when the level of an index well falls below a certain trigger level. The plan calls for an eventual pumping rate from the aquifer of 400,000 AF/yr and claims that this rate would promote water conservation, maximize the beneficial use aquifer water, protect water quality and aquatic and wildlife habitat, and provide for instream and bays and estuaries uses.

The TWC plan calls for a flow of 100 cfs at Comal Springs at least 80% of the time, except during severe droughts. It is not likely that this goal can be met even when the proposed pumping reductions are implemented. The ecosystems in the springs, rivers, and estuaries are most sensitive to drought periods. It is important to have guaranteed daily flow levels during these periods, not annual flow levels. In order to effectively protect the Edwards aquifer and its downstream environment, pumpage needs to be limited to 200,000 AF/yr. This fact is recognized by the TWC but its realization is not considered feasible. Since limiting the pumpage to this level is considered to be unrealistic, even after conservation measures are taken, the only option is the use of alternative water resources.

Finally, the Edwards aquifer is neither a typical river nor a typical aquifer, though it probably resembles an underground river more closely than an aquifer.

## 6.4 MODELING ASPECTS

In the refined TWDB model, simulated flow at San Marcos Springs is about 30% too low due to modeling error. More work must be done to simulate local flow components adequately. Simulated flow at Comal Springs is modeled more accurately, but it is more sensitive than flow at San Marcos Springs due to uncertainty in pumpage and recharge estimates. In either case, we cannot expect the accuracy of simulated springflows to be better than the accuracy of the pumpage and recharge estimates. There is less than a one-to-one correspondence between pumpage reductions and springflow increases. Thus, to increase flow at San Marcos and Comal Springs by a certain amount, pumping must be reduced by an even greater amount. Based on the TWDB model, the proposed interim management plan does not come close to providing for adequate flow as specified by the TWC management plan (100 cfs) at Comal Springs during a repeat of the drought of record. The springs will likely go dry for extended periods during the next severe drought.

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