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Climate-change impacts in a regional karst aquifer, Texas, USA

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Abstract

Climate-change scenarios were created from scaling factors derived from several general circulation models to assess the likely impacts of aquifer pumping on the water resources of the Edwards Balcones Fault Zone (BFZ) aquifer, Texas, one of the largest aquifer systems in the United States. Historical climatic time series in periods of extreme water shortage (1947–1959), near-average recharge (1978–1989), and above-average recharge (1975–1990) were scaled to $2 \times CO_2$ conditions to create aquifer recharge scenarios in a warmer climate. Several pumping scenarios were combined with $2 \times CO_2$ climate scenarios to assess the sensitivity of water resources impacts to human-induced stresses on the Edwards BFZ aquifer. The $2 \times CO_2$ climate-change scenarios were linked to surface hydrology and used to drive aquifer dynamics with alternative numerical simulation models calibrated to the Edwards BFZ aquifer. Aquifer simulations indicate that, given the predicted growth and water demand in the Edwards BFZ aquifer region, the aquifer's ground water resources appear threatened under $2 \times CO_2$ climate scenarios. Our simulations indicate that $2 \times CO_2$ climatic conditions could exacerbate negative impacts and water shortages in the Edwards BFZ aquifer even if pumping does not increase above its present average level. The historical evidence and the results of this article indicate that without proper consideration to variations in aquifer recharge and sound pumping strategies, the water resources of the Edwards BFZ aquifer could be severely impacted under a warmer climate.

Keywords: Climate change; Ground water; Spring flow; Regional hydrology; Karst aquifer; Streamflow; Recharge; Spring flow; Numerical simulation

1. Introduction

The Edwards Balcones Fault Zone (BFZ) aquifer was recently identified as one of the regional watersheds most vulnerable to climate-change impacts in the United States (Loáiciga et al., 1996a). The Edwards BFZ aquifer region was deemed very vulnerable to climate-change impacts for the following reasons: (1) the region is largely dependent on the aquifer to meet municipal, agricultural, industrial/military, and recreational water demands, with limited large-scale alternative water supplies, which are subject to large climatic variability; (2) there is a strong linkage between climatic inputs—precipitation to be specific—and regional hydrology, through the conversion of rainfall to runoff and runoff to aquifer recharge by streambed seepage; (3) the historical climatic record shows large variability in precipitation

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Nomenclature

ACF	Appalachicola–Chatahootchee–Flint
AFY	acre-ft per year (= 1233 m^3/year)
ASCE	American Society of Civil Engineers
BFZ	Balcones Fault Zone
cfs	cubic ft/s (= 35.33 m^3/s)
CCC	Canadian Climate Centre
CO_2	carbon dioxide
EAA	Edwards Aquifer Authority
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GISS	Goddard Institute for Space Studies
GWSIM	Ground Water Simulation Model
OSU	Oregon State University
STATSGO	State Soil Geographic Data Base
SWTSU	South West Texas State University
TWDB	Texas Water Development Board
UKMO	United Kingdom Meteorological Office
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USFS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VEMAP	Vegetation/Ecosystem Modeling and Analysis Project

and the occurrence of occasional multiyear droughts (North et al., 1995) which can reduce natural aquifer recharge to negligible levels (e.g. 1947–1959 drought); (4) historical ground water extraction exhibits an increasing trend for the last 65 years as a result of economic and population growth, a pattern that is predicted to continue at least until year 2050 (Texas Water Development Board (TWDB), 1997); (5) the aquifer supports unique aquatic habitats with a variety of endangered species which face extinction under current trends of ground water exploitation (United States Fish and Wildlife Service (USFWS), 1996); and (6) the local, state, and federal institutional framework for resolving water management issues in the Edwards BFZ aquifer is mired in a complex web of technical, scientific, and legal uncertainties. With this background of existing regional-scale water resources, ecological, and institutional problems, this article presents the results of an analysis of the Edwards BFZ aquifer's vulnerability to climate change. A new methodology to link large-scale climatic processes to basin-scale ground water dynamics is developed and applied in this work (see a review of water-resources related climate-change articles in Gleick, 1989; Lettenmaier and Gan, 1990; Panagoulia, 1992; Loáiciga et al., 1996b).

1.1. Organization of the article

The remainder of Section 1 provides a physical description of the Edwards BFZ aquifer. Section 2 describes our approach to scale historical climate series (precipitation, temperature, streamflow) to climatic conditions expected to occur once the atmospheric concentration of carbon dioxide (CO_2) reaches twice the 355 ppmv level that prevailed in the (reference) year 1990 (i.e. once the standard $2 \times CO_2$ climate scenario sets in Houghton et al., 1995). Section 3 presents aquifer simulations under $2 \times CO_2$ climate scenarios and a range of pumping strategies. Climate scenarios were generated by means of a general circulation model (GCM) developed by the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Aeronautics and Space Administration (NASA), i.e. the GFDL R30 GCM, which has been used in the past to simulate $2 \times CO_2$ climates scenarios in Texas (North et al., 1995) and was available to members of the research team. The GFDL R30 GCM predicts enhanced streamflow under $2 \times CO_2$ relative to other leading GCMs. In this respect, the aquifer impacts assessed in Section 3 were less severe than what they would have been if other GCMs had been used in conjunction with the numerical ground water model that was implemented to simulate detailed aquifer impacts of climate change. The TWDB's finite-difference ground water simulation model IV (GWSIM IV, Thorkildsen and McElhaney, 1992) was implemented in Section 3. Section 4 implements a multi-tank/lumped-parameter ground water model developed by Wanakule and Anaya (1993), and modified by Watkins (1997), in conjunction with climate-forcing data from six GCMs. The six climate models were: (i) the Canadian Climate Center (CCC); (ii) and (iii) the GFDL R15 with and without flux corrections; (iv) the Goddard Institute for Space Studies (GISS); (v) the Oregon

State University (OSU); and (vi) the United Kingdom's Meteorological Office (UKMO) GCMs. The main objective of Section 4 is to identify broad trends of Edwards BFZ aquifer's springflows and hydraulic heads using historical ground water pumping strategies but considering a range of alternative GCM-generated climate scenarios. Conclusions are presented in Section 5.

1.2. The physical setting in the Edwards BFZ aquifer

Fig. 1 shows the location of the Edwards BFZ aquifer. The Edwards BFZ aquifer lies between two physiographic provinces—the Edwards Plateau and the Gulf Coast Plain—of Texas. The Balcones Fault Zone (BFZ) is a system of complex faults which trend in a east-northeast direction. The BFZ is marked by a prominent escarpment which generally rises from an altitude of 600–900 ft (1 ft = 0.305 m) along the sloping lowlands of the Gulf Coast Plain, to an altitude of 1400–2300 ft in the uplands of the Edwards Plateau. The geologic and hydrogeologic setting of the Edwards BFZ aquifer has been described by several authors (see, e.g. Garza, 1964; Rose, 1972; Puente, 1978; Maclay and Small, 1984; Maclay and Land, 1987; LBG-Guyton and Associates, 1995). The Edwards BFZ aquifer is contained within nine river basins which are used for studies of water balance and ground water recharge by the United States Geological Survey (USGS) and other local agencies (Puente, 1978; Edwards Aquifer Authority (EAA), 1996). Cited from westernmost to easternmost locations, the river basins are (with their areas written within parentheses, 1 $mi^2 = 2.59$ km^2): (1) Nueces (1861 mi^2); (2) Frio (631 mi^2); (3) Sabinal (241 mi^2); (4) Seco-Hondo creek (317 mi^2); (5) Medina (634 mi^2); (6) Helotes-Salado creek (137 mi^2); (7) Cibolo-Dry Comal creek (274 mi^2); (8) Guadalupe (1648 mi^2); and (9) Blanco (412 mi^2).

The Edwards BFZ aquifer is comprised of two hydrogeologic regions: a recharge area (shaded area in Fig. 1), and a fresh-water, confined, ground water flow zone. The recharge and confined areas are estimated to be about 1100 and 5009 mi^2 in area, respectively. Runoff which originates in the catchment area (within the Edwards Plateau) flows through the recharge area in the Edwards BFZ aquifer. There, streams flow through outcropping Edwards aquifer formations and a large portion of their streamflow percolates to recharge the fresh water aquifer. Average yearly recharge from 1934 to 1995 (which includes the drought period 1947–1959) was 674,000 acre-ft per year (1 acre-ft per year = 1 AFY = 1233 m^3), while post-drought, 1960–1995, annual average recharge was 800,000 AFY (EAA, 1996). The southern-southeastern boundary of the Edwards BFZ aquifer freshwater zone is a saline water–fresh-water interface. This interface is called the "bad-water" line. There is a pronounced change in the mineral content of ground water, from freshwater conditions (about 350 mg/l) in the Edwards limestone formation to over 1000 mg/l total dissolved solid (TDS) across the bad-water line (Maclay and Land, 1987).

Ground water moves generally from west to east and discharges in a number of large springs, of which the Comal and San Marcos springs are the most prominent. These ground water fed springs have average springflows of 284 cfs (205,000 AFY) and 170 cfs (=123,000 AFY), respectively (USFWS, 1996). Temperature of the springflow is uniform throughout the year, having a mean water temperature of 23.3 and 22°C at Comal and San Marcos springs, respectively. Flow uniformity, in volumetric rate and temperature, as well as alkaline water chemistry, have created one of the most diverse aquatic ecosystems in the southwestern United States (Longley, 1981; USFWS, 1996). It includes the Edwards BFZ aquifer and the ecosystems associated with the Comal and San Marcos springs and related springs runs, lakes, rivers, and caves. These unique ecosystems supported by the Edwards BFZ aquifer underground habitat and spring flows have been impacted by ever-increasing ground water pumping and development/recreational activities that affect water quality and modify species habitat in multiple ways (USFWS, 1996). Species listed as endangered in the Edwards BFZ aquifer by the federal government are: the San Marcos gambusia (*Gambusia georgei*, a fish species), the fountain darter (*Etheostoma fonticola*), the Texas wild-rice (*Zizania texana*), and the Texas blind salamander (*Typhlomolge rathbuni*). In addition, the San Marcos salamander (*Euricea nana*) is listed as threatened (Campbell, 1995; USFWS, 1996). Protection of these species from extinction lies at the heart of the management and regulatory issues concerning ground water pumping in the Edwards BFZ aquifer.

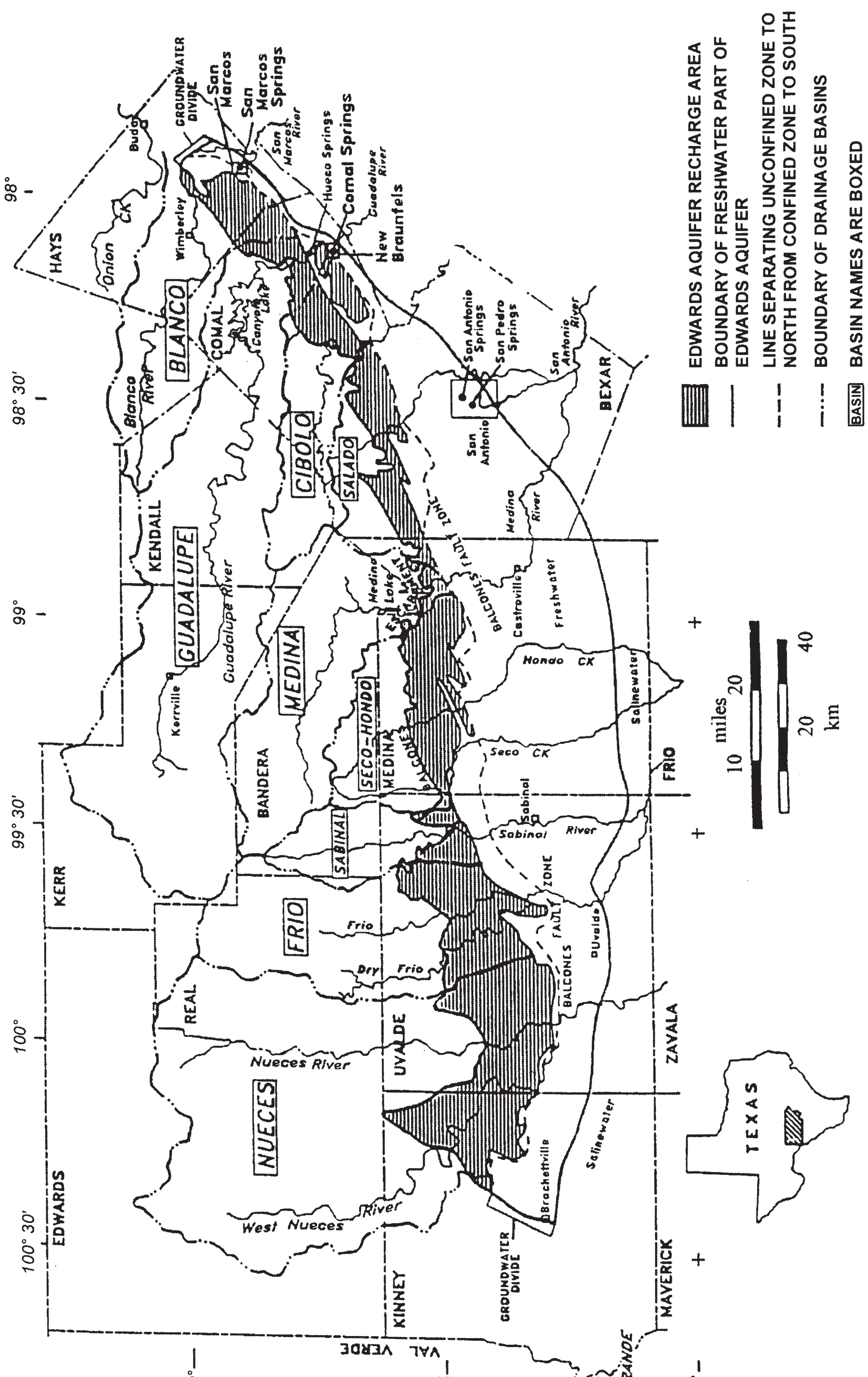

Fig. 1. Map of the Edwards BFZ aquifer (after USFWS, 1996).

2. $2\times CO_2$ climate scenarios in the Edwards BFZ aquifer

2.1. The use of scaling factors to generate climate change scenarios

Climate change is quantified in terms of scaling factors that involve $1\times CO_2$ and $2\times CO_2$ GCM-simulated temperature, precipitation, and streamflow. The $1\times CO_2$ GCM simulation corresponds to the 1990 CO_2 atmospheric concentration (≈355 ppmv). Scaling factors are used in two ways to generate climate change scenarios from historical time series. The first consists of multiplying a historical time series by the corresponding scaling factor (or scaling ratio in this case). Using precipitation (P) as an example, the equation used to generate the $2\times CO_2$ precipitation scenario is as follows:

$$P_{2\times CO_2\ \text{scenario}} = \frac{P_{2\times CO_2}}{P_{1\times CO_2}} P_{\text{historical}} \quad (1)$$

If the GCM-simulated $P_{1\times CO_2}$ and $P_{1\times CO_2}$ are unbiased and independent estimators of precipitation under $1\times CO_2$ and $2\times CO_2$ conditions, respectively, then, the expected value of the estimated precipitation $P_{2\times CO_2\ \text{scenario}}$ is equal to the $2\times CO_2$ precipitation mean ($\mu_{2\times CO_2}$), i.e. $P_{2\times CO_2\ \text{scenario}}$ is an unbiased estimator also. It is implied in the latter statement that $P_{\text{historical}}$ and $P_{1\times CO_2}$ have identical expected values which are both equal to the historical mean. Streamflow is scaled in a manner similar to that used to scale precipitation.

Temperature scaling is based on the difference between the $1\times CO_2$ and $2\times CO_2$ temperatures, $T_{2\times CO_2} - T_{1\times CO_2}$, that is applied to the historical temperature ($T_{\text{historical}}$). Specifically, the global-warming scenario ($T_{2\times CO_2}$ scenario) is constructed according to the following equation:

$$T_{2\times CO_2\ \text{scenario}} = \{T_{2\times CO_2} - T_{1\times CO_2}\} + T_{\text{historical}} \quad (2)$$

If $T_{1\times CO_2}$ and $T_{1\times CO_2}$ are unbiased estimators of temperature under $1\times CO_2$ and $2\times CO_2$ conditions, then the expected value of the estimated scenario $T_{2\times CO_2\ \text{scenario}}$ equals the $2\times CO_2$ mean temperature, i.e. $T_{2\times CO_2\ \text{scenario}}$ is an unbiased estimator also. This assumes that the expected values of $T_{1\times CO_2}$ and $T_{\text{historical}}$ are both equal to the historical mean temperature.

The rationale behind the use of scaling factors is that—although GCMs may not accurately estimate the local statistics of regional climate variables—their internal consistency and strong physical basis may provide plausible estimates of their ratios and differences. The climate scenarios generated with the scaling ratios and differences in combination with historical time series are then used to drive aquifer simulation models. Results of climate-change impacts in the Edwards BFZ aquifer region are presented in Sections 3 and 4. A different set of climate-scaling factors is considered in each of those sections. The two sets of climate-scaling factors are discussed next (see Loáiciga et al., 1996b for an in-depth discussion of GCM limitations).

2.2. Climate-change scaling factors in the Edwards BFZ aquifer: GFDL R30 simulations

The physical basis of the GFDL R30 was described in Manabe and Wetherald (1987). The horizontal resolution of the model is 2.25° latitude by 3.75° longitude and the GCM features nine unevenly spaced vertical layers. Multi-year GFDL R30 simulation results for the grid cell were within 29.06°N to 31.31°N and 95.87°W to 99.62°W were used in this work to develop the climate-scaling factors with which to drive ground water dynamics in the Edwards BFZ aquifer based on GWSIM IV (see Section 3 for an implementation of GWSIM IV). The chosen grid cell includes the Edwards BFZ aquifer (which lies roughly between 29.1°N to 31.0°N and 97.4°W to 100.4°W). Table 1 shows the monthly average scaling factors for temperature, precipitation and streamflow generated by the GFDL R30 at the cell that encompasses the Edwards BFZ aquifer. Only the streamflow scaling factors are needed to drive GWSIM IV, as shown in Section 3.

2.3. Climate-change scaling factors in the Edwards BFZ aquifer: the vegetation/ecosystem modeling and analysis project (VEMAP) database

The VEMAP database consists in part of historical precipitation and temperature measured during the period 1895–1993. Precipitation was measured at 8500 stations and temperature at 5500 stations in the coterminous United States. A kriging technique was applied to the historical precipitation and temperature

Table 1
Average monthly scaling factors (temperature, precipitation, and runoff) from GFDL R30 runs at the grid cell that overlies the Edwards BFZ aquifer (see text for the cell's coordinates)

Variable	January	February	March	April	May	June	July	August	September	October	November	December
Temperature	1.56	1.42	1.39	1.28	1.17	1.17	1.00	1.04	1.07	1.11	1.30	1.54
Precipitation	1.21	0.92	0.81	0.90	0.55	3.52	3.10	4.46	0.63	1.73	0.76	1.60
Streamflow	1.51	0.78	0.69	0.31	0.10	1.00	1.00	3.5	1.00	3.5	1.94	2.48

data to yield estimates gridded at a 0.5° latitude × 0.5° longitude resolution (Rosenbloom and Kittel, 1996; Kittel et al., 1997). The derived 0.5° × 0.5° gridded data set is a temporally complete (i.e. there are no data gaps in time) and geographically realistic representation of the historical climate record. The VEMAP gridded precipitation and temperature data for the Edwards BFZ region were used to calibrate a physically based climate-hydrologic model that simulates ground water recharge in an aquifer simulation model for the Edwards BFZ aquifer described in Section 4.

The VEMAP data set also contains scaling factors for precipitation and temperature generated by seven GCMs (i.e. the CCC, GISS, GFDL R15 with flux corrections, GFDL R15 without flux corrections, GFDL R30, OSU, and UKMO GCMs). The scaling factors applicable to the Edwards BFZ aquifer region are discussed in Section 4. Those factors were used to scale historical time series and simulate climate scenarios in a manner analogous to that implied by Eqs. (1) and (2). The scaling factors obtained from alternative GCMs allows a comparison of climate-change impacts in the Edwards BFZ aquifer region based on a representative cross section of the leading climate simulation models currently in use.

3. Results of climate changes impacts in the Edwards aquifer region: the Edwards balcones fault zone (BFZ) aquifer model simulations

3.1. Overview of the Edwards BFZ aquifer model (GWSIM IV)

The Edwards Aquifer model is a modified version of the two-dimensional, finite-difference, ground water simulation program originally developed by Prickett and Lonquist (1971). The model was modified in 1974 by the TWDB to simulate ground water flow and springflow in the Edwards Aquifer Balcones Fault Zone and was renamed Ground Water Simulation Program, or GWSIM (see Klemt et al., 1979). Knowles (1983) updated GWSIM under the title GWSIM IV. The partial differential equation that describes non-steady flow in GWSIM IV is given by (Knowles, 1983; see also Klemt et al., 1979, for further details):

$$\frac{\partial}{\partial x}\left(T(x,y)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T(x,y)\frac{\partial h}{\partial y}\right) = S(x,y)\frac{\partial h}{\partial t} + W(x,y) \quad (3)$$

in which T is the aquifer transmissivity ($L^2\ t^{-1}$), h the hydraulic head (L), S the storage coefficient (dimensionless), t the time (T), W the net ground water flux per unit area ($L\ t^{-1}$, which includes pumping, springflow, and recharge, in general), and x, y the rectangular coordinates (L). The ratio of the lateral extent to the vertical dimension in the Edwards BFZ aquifer is larger than 10^2. Therefore, the ground water flow is well described as a two-dimensional regime. Eq. (3) is discretized in the GWSIM IV model according to a block-centered finite-difference scheme developed by Prickett and Lonquist (1971). The simulation time step is one month, and the numerical grid consists of 31 rows and 80 columns, for a total of 2480 cells of variable size that encompass the areal extent of the Edwards BFZ aquifer (the numerical grid of GWSIM IV is shown in Fig. 2).

Thorkildsen and McElhaney (1992) refined GWSIM IV and analyzed the response of springflow to ground water pumping scenarios in the Edwards Aquifer Balcones Fault Zone. The re-calibrated version of GWSIM IV developed by Thorkildsen and McElhaney (1992) is what is herein called the Edwards BFZ Aquifer model. In addition to hydraulic head, the Edwards BFZ aquifer model simulates discharge at several of the largest springs in the Edwards BFZ aquifer, such as the Comal, San Marcos, San Pedro, San Antonio, and Leona springs (the locations of several springs are shown in Fig. 1).

The GWSIM IV numerical grid, shown in Fig. 2, distinguishes among no-flow boundary cells, outcrop or recharge-zone cells, and artesian cells. The outcrop cells overlie the recharge region, wherein ground water recharge accrues to the unconfined aquifer. The artesian cells overlie the confined region of the aquifer, which consists of highly permeable, karstified, rocks known generically as the Edwards limestone formation. Most of the high-quality ground water pumped from the Edwards BFZ aquifer is extracted in the artesian region. No-flow cells are located along the perimeter of the aquifer. In the northern perimeter of the outcrop zone the no-flow cells approximate conditions created by geologic faults that act as barriers to subsurface flow. The southern, no-flow, boundary of the Edwards BFZ aquifer coincides with the so-called "bad-water" line (see above description of the physical setting in the Edwards BFZ aquifer region).

3.2. $2 \times CO_2$ scaling of ground recharge in the Edwards BFZ aquifer model

A key aspect of this study is how to scale historical ground water recharge to $2 \times CO_2$ conditions. To explain the historical to $2 \times CO_2$ scaling, a brief review of the method to calculate recharge in the Edwards BFZ aquifer is in order. The method to calculate recharge in the Edwards BFZ aquifer was developed by Puente (1978), and it is used by the United States Geological Survey (USGS) to calculate monthly recharge in the aquifer. The USGS recharge method (Puente, 1978) calculates recharge in the outcrop (recharge) region from a water balance of the streamflow crossing the recharge region. In gauged basins, streamflow (expressed in units of volume per unit time) is measured at an upper gage (i.e. upstream of the zone of analysis) and at a lower gage (located downstream of the zone of analysis). Let R denote monthly recharge in any of the nine river basins of the Edwards BFZ aquifer (in units of volume of water per month), Q_U be the streamflow passing through the upper stream gage; Q_L be the measured streamflow at the lower stream gage; and Q_I denote the streamflow generated in the drainage area intervening between the two gaging stations. Q_I is not measurable and must be estimated. Recharge R is given by the following water balance equation:

$$R = Q_U + Q_I - Q_L \tag{4}$$

The streamflow, Q_I, is estimated based on the assumption that streamflow is generated in an amount that is proportional to the size of the drainage area from which it derives and to the ratio of precipitation P_I/P_U, where P_I and P_U represent the average monthly precipitation in the drainage area between upper and lower gages and the average monthly precipitation in the drainage area above the upper gage, respectively. Specifically, the USGS recharge method (Puente, 1978) assumes that Q_I is equal to that portion of streamflow generated by individual storms at the upper gage ($\equiv Q_{2U}$) scaled by the ratios A_I/A_U and P_I/P_U. A_I is the drainage area between the upper and lower stream gages and A_U is the drainage area above the upper gage. Q_{2U} represents the streamflow generated by storms at the upper gage within any month: it is that portion of the total streamflow Q_U in excess of the baseflow that would have existed if the storms had not occurred. Q_{2U} is estimated in Puente (1978) by means of a hydrograph separation scheme and from empirical estimates of the baseflow at the upper gage arising from water storage in the Glen Rose aquifer above the recharge zone. Thus, Q_I is estimated by:

$$Q_I = \frac{A_I}{A_U}\frac{P_I}{P_U}Q_{2U} \tag{5}$$

Substitution of Eq. (5) for Q_I into that for recharge R (Eq. (4)) results in the following:

$$R = Q_U + Q_{2U}\frac{A_I}{A_U}\frac{P_I}{P_U} - Q_L \tag{6}$$

Eq. (6) embodies two important implications: (1) it is the ratio of precipitation, rather than its individual value, that controls the generation of streamflow in the drainage area between gages. Thus, if the $2 \times CO_2$ precipitation were obtained by scaling each of the historical time series (i.e. P_I and P_U) by the ratio $P_{2\times CO_2}/P_{1\times CO_2}$, it follows that the scaling would leave P_I/P_L unaltered; and (2) $2 \times CO_2$ streamflow is obtained by scaling the historical streamflow by the ratio $Q_{2\times CO_2}/Q_{1\times CO_2}$. Therefore, Eq. (6) implies that recharge is scaled by the same ratio. The monthly

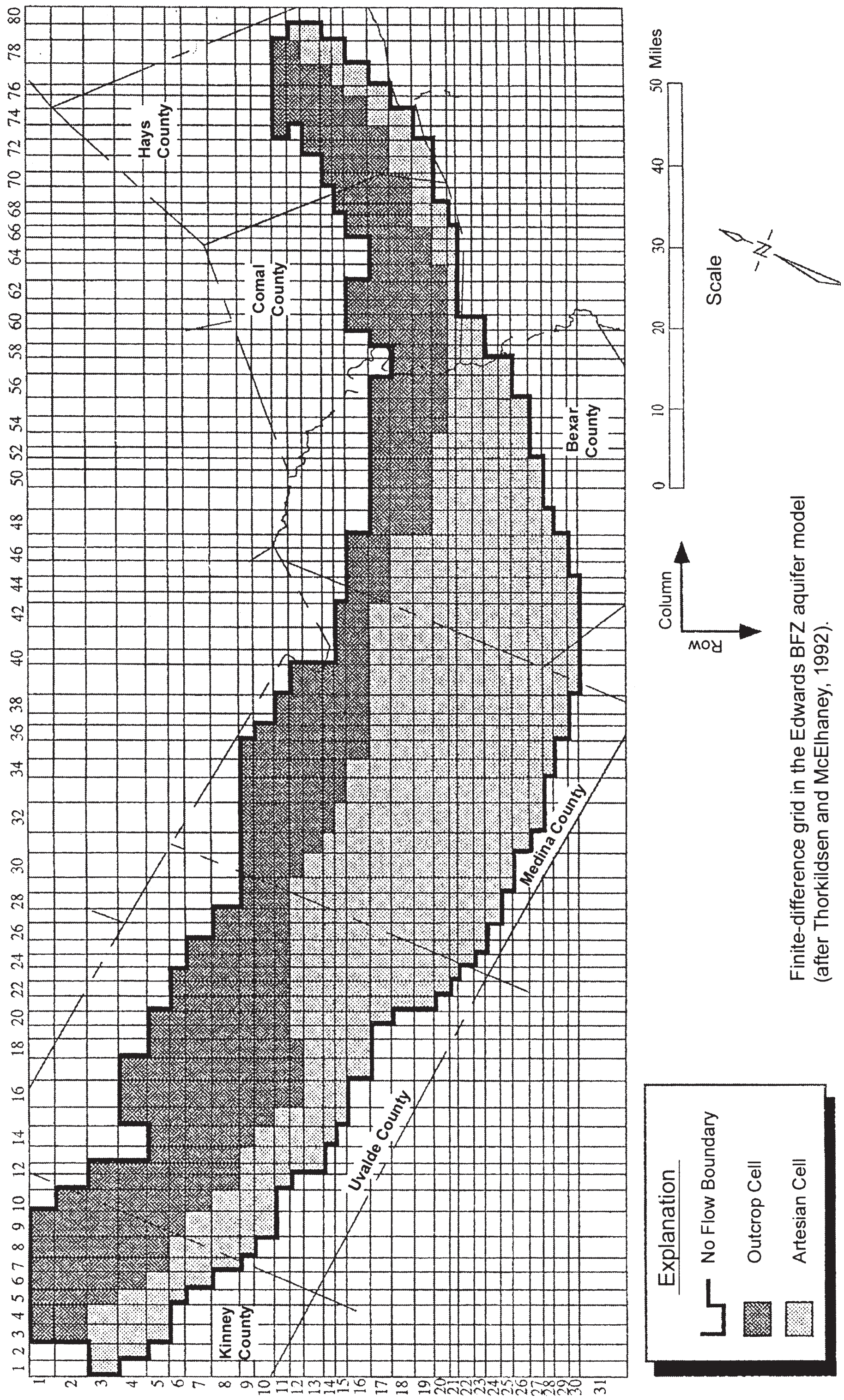

Fig. 2. Finite-difference grid for the Edwards BFZ aquifer (after Thorkildsen and McElhaney, 1992; see Fig. 1 for location of grid relative to surrounding counties in the study area).

scaling ratios for streamflow, $Q_{2\times CO_2}/Q_{1\times CO_2}$, applied to ground water recharge in the Edwards BFZ aquifer were obtained from the GFDL R30 simulations and are listed in Table 1.

Monthly ground water recharge from 1934–1996 broken down by river basin (there are nine basins in the Edwards BFZ aquifer) was obtained from the USGS San Antonio, Texas, Office (David Brown, hydrologist, personal communication, 1998). Ground water recharge in each river basin must be distributed among the finite-difference cells that make up the recharge region of each river basin (and shown in Fig. 2). The gridded ground water recharge for the Edwards BFZ aquifer for the period 1934–1996 was obtained from the TWDB (Paul McElhaney, geologist, personal communication, 1998).

3.3. Ground water pumping: historical and forecasted

Human-induced stresses on the Edwards aquifer are exerted primarily through pumping of ground water. In the period 1975–1995, the annual pumping from the Edwards BFZ aquifer averaged 430,000 acre-ft (1 acre-ft = 1 AF = 1233.5 m^3) (Edwards Aquifer Authority (EAA), 1996). Monthly historical ground water pumping data from 1934 to 1996, broken down cell by cell of the Edwards Aquifer model's grid, were obtained from the TWDB (Paul McElhaney, geologist, personal communication, 1998). Ground water pumping forecasts for year 2050 (TWDB, 1997) were assumed to be consistent with the $2 \times CO_2$ climatic scenario. The 2050 ground water withdrawal forecasts for the Edwards BFZ aquifer are the most forward reaching official estimates of ground water extraction in the study area, and equal 636,000 AFY (TWDB, 1997). This compares to a pumping level of 400,000 AFY in 1995 (EAA, 1996).

3.4. Scenarios for aquifer simulation

Several ground water pumping and climate scenarios were simulated with the Edwards BFZ aquifer model. The combination of pumping and climate scenarios was designed to reveal the range of possible impacts that the Edwards BFZ aquifer might undergo relative to observed historical patterns of ground water pumping impacts. The chosen indicators of ground water pumping impacts are the springflows at Comal and San Marcos springs. They are unequivocal indicators of the status of ground water in the Edwards BFZ aquifer.

Two historical periods were used to construct the aquifer simulation scenarios. The first period is from January 1947 to December 1959 (for a total of 156 months). The second period goes from January 1978 to December 1989 (for a total of 144 months). These two periods have been identified by the TWDB (Thorkildsen and McElhaney, 1992) as being representative of critically dry (1947–1959) and average (1978–1989) climatic conditions. The 1947–1959 period includes the most severe drought on record and it is used to evaluate "worst-case" climatic scenarios in the Edwards BFZ aquifer. The average annual recharge in the Edwards BFZ aquifer between 1947 and 1959 was 449,000 AFY. The period 1978–1989 had average climatic conditions, with no interannual severely dry or wet protracted climatic conditions. Average annual recharge during 1978–1989 was 770,000 AFY. It was during this latter period, however, that ground water pumping in the Edwards BFZ aquifer rose to historically high levels as a result of urban and economic growth in the study area. In year 1989, for example, ground water pumping in the Edwards BFZ aquifer reached an all-time high of 524,000 AF.

Several aquifer simulation scenarios were based on the 1947–1959 drought period. Of those, three scenarios were used to construct a range of climate change response. The first scenario, herein named scenario D1 ("drought 1"), scales the historical recharge during the 1947–1959 period by means of the monthly coefficients $Q_{2\times CO_2}/Q_{1\times CO_2}$ obtained from the GFDL R30 simulations cited above. The scaled time series of monthly aquifer recharge is the recharge estimated to occur during a severe drought under $2 \times CO_2$ conditions. The pumping applied in scenario D1 was the TWDB (1997)forecast for year 2050 of 636,000 AFY. The second scenario, which is named scenario D2, scales historical recharge during the 1947–1959 period to $2 \times CO_2$ conditions in a fashion similar to scenario D1. Pumping was set equal to zero in scenario D2. The selection of pumping equal to the 2050 forecast and to zero in scenarios D1 and D2, respectively, is intended to show the range of aquifer responses varying from the no human impact case to the case expected to occur if growth conditions turn out to be as currently forecasted. Thus, scenarios D1 and D2 are intended to define a range of aquifer responses under $2 \times CO_2$ climatic conditions. The third scenario constitutes the aquifer response simulated during the period 1947–1959 with historical recharge and pumping, herein termed the "historical" scenario. The historical scenario was included to compare the change in climatic conditions from historical to $2 \times CO_2$-based scenarios. Other pumping scenarios, between the D1 and D2 cases, were also simulated with the 1947–1959 base drought period scaled to $2 \times CO_2$ conditions to identify intermediate aquifer responses. Simulation results will be discussed below.

Several aquifer simulation scenarios were considered based on the 1978–1989 near-average recharge period. Among those, three aquifer simulation scenarios were used to define a range of aquifer responses. The first scenario, which is called scenario A1 ("average 1"), scales monthly 1979–1989 historical recharge by the monthly $Q_{2\times CO_2}/Q_{1\times CO_2}$ coefficients and applies the 2050 year pumping forecast of 636,000 AFY. Scenario A1 is aimed at revealing the aquifer response if "average" climatic were to occur under $2 \times CO_2$ climate. The 636,000 AFY pumping reflects aquifer exploitation impacts if growth forecasts are realized. The second scenario, or scenario A2, scaled monthly 1978–1989 recharge to $2 \times CO_2$ conditions as done in scenario A1. Pumping was set equal to zero in scenario A2. The objective was to develop an envelope of aquifer responses under $2 \times CO_2$ ground water recharge whose boundaries are defined by the no (human) impact, or zero pumping, scenario and the forecasted pumping in year 2050. The third scenario, the "historical" scenario, was based on historical recharge and pumping for the period 1978–1989. Results under the historical scenario were included to compare the historical impacts to those that might arise under $2–CO_2$ conditions. Other pumping scenarios, between the A1 and A2 cases, were also simulated with the 1978–1989 base period scaled to $2 \times CO_2$ conditions to identify intermediate aquifer responses. Simulation results will be discussed below.

3.5. Results of scenario simulations: base period 1947–1959 scaled to $2 \times CO_2$ recharge

Fig. 3 shows the springflow at Comal springs associated with the historical simulation and scenarios D1 and D2. In addition, Fig. 3 depicts a reference minimum springflow of 100 cfs (=5950 AF for a 30-day month). Springflow minima for Comal and San Marcos springs have been developed by the USFWS (1996)and those vary depending on the endangered or threatened species affected by low springflow. The 100-cfs reference has been adopted herein as a simplified criterion to be applied to both Comal and San Marcos springs. This reference value is used only as a measure of the relative severity of impacts caused by pumping scenarios and does not affect simulation results. From Fig. 3 it can be concluded that: (1) if a severe drought were to occur under $2 \times CO_2$ conditions and the forecasted year 2050 pumping of 636,000 AFY is applied (these conditions define scenario D1), Comal springs would dry up 20 months after pumping started; (2) the reference 100 cfs minimum springflow would be first violated 15 months after the beginning of pumping, and springflow would remain under the 100 cfs level thereafter; (3) a zero pumping strategy (scenario D2) would result in Comal springflow of no less than 250 cfs (=14,900 AF for a 30-day month) at all times; (4) the impacts of year 2050 pumping would be much more severe than those observed during the 1947–1956 drought. For example, while the historical springflow recovered after 125 months, the scenario D1 simulation shows that Comal springflow would vanish for all but the first two years of the drought period.

Fig. 4 displays the evolution of San Marcos springflow produced by scenarios D1 and D2 as well as by the historical simulation. The reference minimum springflow of 100 cfs (5950 AF for a 30-day month) is also shown in the Fig. 4. The range of springflow is clearly defined by the trajectories associated with scenarios D1 and D2. The following conclusions can be drawn from Fig. 4: (1) San Marcos springflow falls frequently below the minimum springflow under zero pumping (scenario D2); (2) with year 2050 pumping (scenario D1) the San Marcos springflow does not dry up until after the 100th month and it begins to recover after the 130th month; (3) the gap in San Marcos springflow created by scenarios D1 and D2 (zero pumping and year 2050 pumping, respectively) is not as wide as the one observed in the springflow range for Comal springflow in Fig. 3. Figs. 3 and 4 imply that the Comal springs are more vulnerable than San Marcos springs to catastrophic impacts, i.e.

Comal springs are susceptible to complete dry out for extended periods of time under scenario D1. Given that San Marcos springflow falls mostly below the minimum reference level under either scenarios D1 and D2 and that Comal springs dry out under scenario D1, one must conclude that the Edwards BFZ aquifer would be severely impacted if a protracted drought were to occur under $2 \times CO_2$ ground water recharge conditions.

3.6. Results of scenario simulations: base period 1978–1989 scaled to $2 \times CO_2$ recharge

Fig. 5 shows the response of Comal springs to the simulation associated with scenarios A1, A2 and the historical scenario. Based upon Fig. 5, the scenario A1 springflow response is similar to that obtained with historical pumping and recharge in the base period (1978–1989), except between month 108 and 132, when scenario A1 led to larger springflows. The scenario A1 (defined by $2 \times CO_2$ recharge and year 2050 pumping) is maintained above the 100 cfs (=5950 AF in a 30-day month) level at all times during the scenario A1 simulation, except for about a six-month period, from month 78 to 84. A comparison of the historical and scenario A1 simulations in Fig. 5 indicates that under $2 \times CO_2$ recharge and year 2050 (636,000 AFY) pumping the Comal springs would be in a condition comparable to that observed in the period 1978–1989. The scenario A2 simulation in Fig. 5 completes the range of Comal springflow response. With the zero pumping implied by scenario A2 Comal springflows would be kept at all times over 400 cfs (23,800 AF in a 30-day month, Fig. 5).

Fig. 6 displays the San Marcos springflow simulations associated with scenarios A1, A2, and the historical scenario. In Fig. 6, the spread of the San Marcos springflow envelope defined by scenarios A1 and A2 is quite narrow. Unlike the Comal springfow response, Fig. 6 shows that the San Marcos springflow falls below the 100 cfs (=5950 AF/month) level frequently, just as it did according to the historical simulation. This pattern is particularly well accentuated between months 60 and 96. The scenario A2, which prescribes no ground water extraction, keeps the San Marcos springflow at or above the 100 cfs mark at all times during the simulation. The results in Fig. 6 indicate that scenario A1 would leave San Marcos springflow in a condition comparable to that associated with the historical simulation for the average-climate conditions of the 1978–1989 base period.

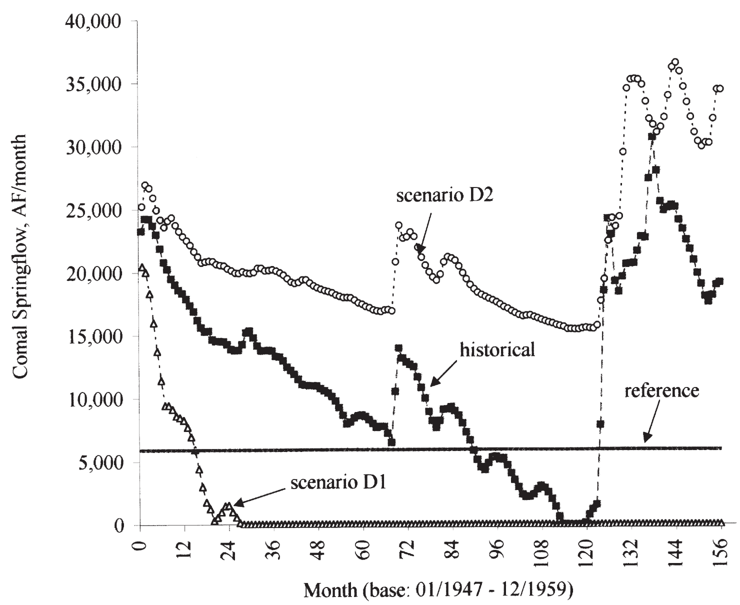

Fig. 3. Comal springflow response to simulations under historical pumping and recharge and under scenarios D1 and D2 (D1: $2 \times CO_2$ climate and year 2050 pumping; D2: $2 \times CO_2$ climate and no pumping; 1947–1959 base drought period; 1 AF = 1233 m^3).

3.7. Implications of scenario-based simulations for Edwards BFZ aquifer management

A number of pumping targets in the Edwards BFZ aquifer are derived next based on the previous scenario-based simulations. These targets are intended to provide a reference baseline for the type of pumping levels that would minimize springflow impacts in the study area under global warming scenarios.

Fig. 7 relates the minimum Comal and San Marcos springflows to average annual pumping under $2 \times CO_2$ climatic conditions. The period 1947–1959 is used as the base period of analysis. Therefore, Fig. 7 embodies springflow-pumping relationships expected to hold in the Edwards BFZ aquifer under severe drought conditions in a warmer planet. It is seen in Fig. 7 that regardless of the level of pumping, San Marcos minimum springflow would be under the reference level of 100 cfs (5950 AF/month). A possible alternative to prevent excessively low San Marcos springflow under severe drought would be to augment springflow artificially (McKinney and Sharp, 1995). This means that surface water supplies (other than springflow) would need to be added to the San Marcos springs. It is possible, at least in theory, that ground water pumped in other regions whose hydraulic heads do not affect San Marcos or Comal springflow could be brought in to enhance their discharge rates. It is unlikely, however, that any additional ground water could be pumped elsewhere under a severe drought without creating another set of local impacts. Springflow augmentation is also complicated by water quality issues. Habitat conservation is not only a function of flow rate, but also of water temperature and chemical characteristics of the spring water (e.g. pH, alkalinity, mineral content). The previous considerations highlight the difficulties of finding adequate water to augment springflow during severe drought. Water conservation is another important tool to reduce ground water pumping in the Edwards BFZ aquifer.

Fig. 7 shows that minimum Comal springflow exceeds the reference level of 100 cfs (=5950 AF/month) only when the pumping is less than 140,000 AFY (defined by point 1 in Fig. 7) if a severe drought were to occur under $2 \times CO_2$ climatic conditions. The 140,000 AFY pumping is less than the recommended sustainable level of 165,000 AFY suggested by Thorkildsen and McElhaney (1992). Evidently, aquifer management options are tightly

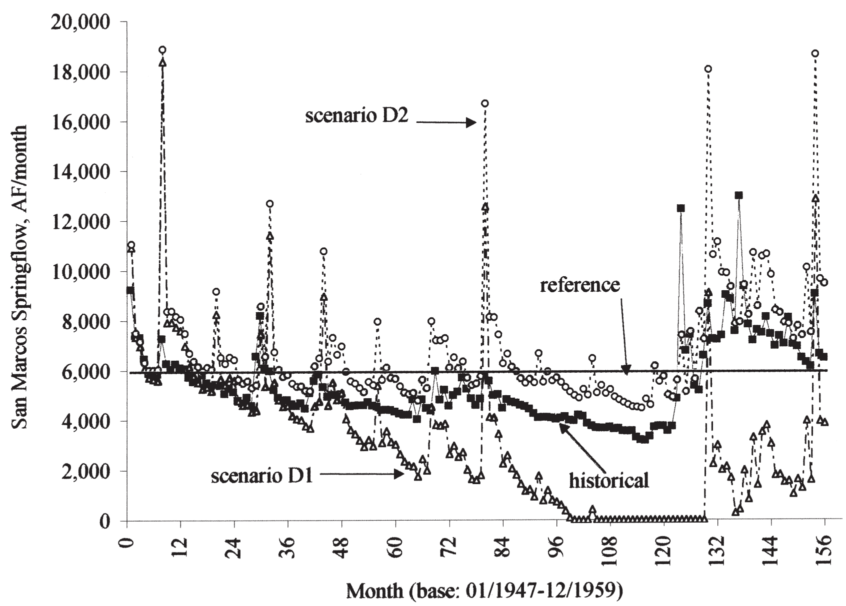

Fig. 4. San Marcos springflow response to simulations under historical pumping and recharge and under scenarios D1 and D2 (D1: $2 \times CO_2$ climate and year 2050 pumping; D2: $2 \times CO_2$ climate and no pumping; 1947–1959 base drought period; 1 AF = 1233 m^3).

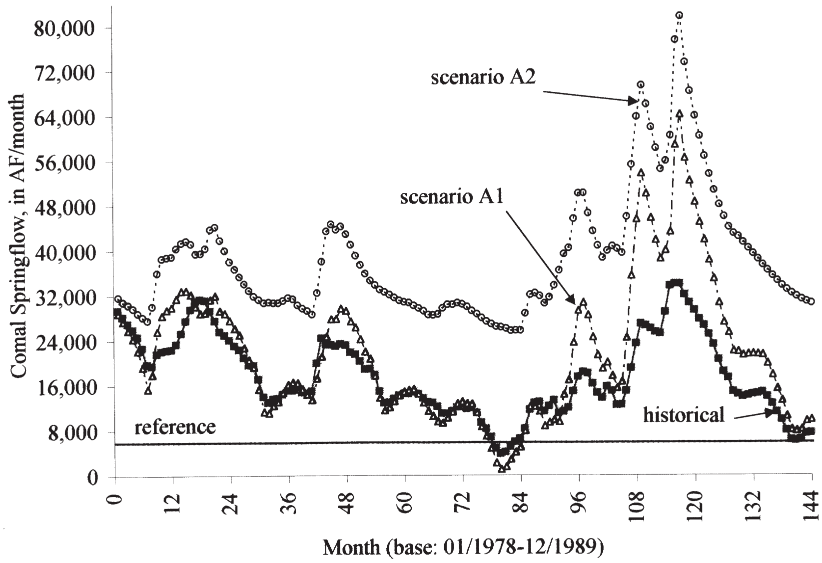

Fig. 5. Comal springflow response to simulations under historical pumping and recharge and under scenarios A1 and A2 (A1: $2 \times CO_2$ climate and year 2050 pumping; A2: $2 \times CO_2$ climate and no pumping; 1978–1989 base period of average recharge; 1 AF = 1233 m^3).

constrained under drought conditions in a warmer climate.

A more favorable management picture arises from Fig. 8, where minimum Comal and San Marcos springflows are plotted as a function of the average annual pumping in the Edwards BFZ aquifer. The base period is 1978–1989, thus implying "average" climate under $2 \times CO_2$ conditions. Points 1 and 2 in

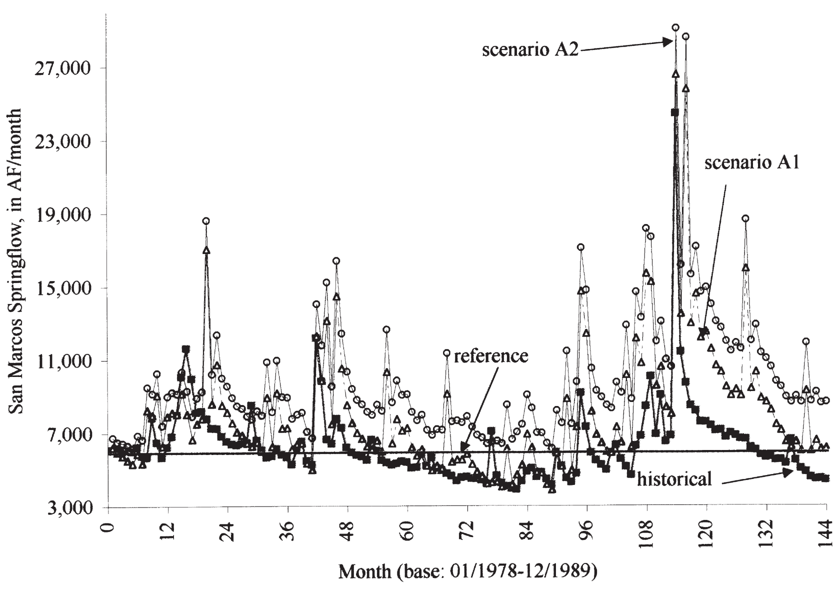

Fig. 6. San Marcos springflow response to simulations under historical pumping and recharge and under scenarios A1 and A2 (A1: $2 \times CO_2$ climate and year 2050 pumping; A2: $2 \times CO_2$ climate and no pumping; 1978–1989 base period of average recharge; 1 AF = 1233 m^3).

Fig. 8 correspond to pumping rates of 539,000 and 61,000 AFY, respectively. Points 1 and 2 define the pumping rates at which minimum Comal and San Marcos springflows, respectively, would reach the 100 cfs reference level. It is seen in Fig. 8 that the minimum San Marcos springflow is not as sensitive to the level of pumping as the minimum Comal springflow is under the "average" $2 \times CO_2$ climatic conditions. Therefore, if low discharge can be tolerated occasionally at San Marcos springs, Fig. 8 indicates that under average $2 \times CO_2$ recharge conditions the pumping in the Edwards BFZ aquifer can be anywhere between 0 and 450,000 AFY. The pumping of 450,000 AFY is associated with minimum San Marcos springflow of approximately 4600 AF/month or 77.3 cfs, which represents a 22.3% reduction from the reference level of 100 cfs. The 450,000 AFY pumping figure is significant because Texas Senate Bill 1477 proposed a maximum pumping of 450,000 AFY until December 31, 2007, and, thereafter, a maximum pumping of 400,000 AFY. If the permissible pumping is extended to 539,000 AFY (point 1 in Fig. 8), then the associated minimum springflows at San Marcos and Comal would be 71.6 and 100 cfs, respectively.

A 400,000 AFY maximum pumping target seems reasonable when examined from the viewpoint of expected impacts under "average" $2 \times CO_2$ climate. It preserves minimum discharge at Comal springs and achieves discharge minima close to the 100 cfs reference level at San Marcos springs during non-drought climatic conditions. The 400,000 AFY target pumping recommended herein during non-drought $2 \times CO_2$ conditions is much lower than the TWDB (1997)forecasted pumping in the Edwards BFZ aquifer of 636,000 AFY by year 2050. The TWDB's forecasted pumping would dry up Comal springs and impose frequent and severe water shortages in San Marcos springs.

A recent draft ground water management plan prepared by the EAA (July 1998, web site http// e~aquifer.com/gmp7-7.html) specifies water supply targets from the Edwards BFZ aquifer during periods of average ground water recharge of 450,000 AFY until year 2010 and of 400,000 AFY thereafter. The EAA's 1998 pumping targets are compatible with our findings provided that ground water recharge is at or near average levels. During drought conditions the situation changes radically. Our previous analysis suggests a maximum pumping target on the order of 140,000 AFY. However, under severe drought conditions there is no management strategy that could

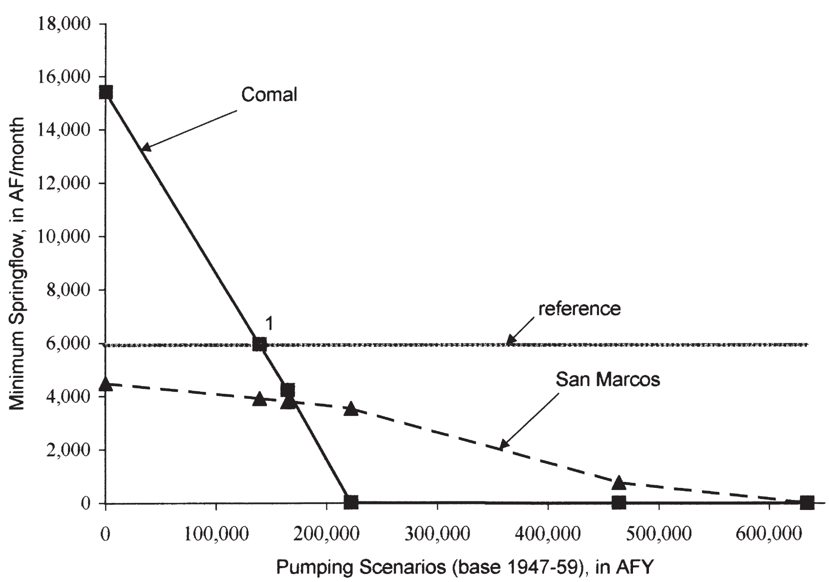

Fig. 7. Minimum Comal and San Marcos springflow as a function of ground water pumping under climate under $2 \times CO_2$ conditions (1947–1959 base drought period; 1 AF = 1233 m^3).

prevent discharge shortages in San Marcos springs. The 140,000 AFY recommended maximum pumping target for drought conditions reflects a compromise to avoid catastrophic impacts (i.e. complete drying out of springflows) on spring discharge and yet provide a minimum level of ground water supply in the Edwards BFZ region. In view of the magnitude of water use forecasts in the Edwards BFZ region by year 2050 issued by the TWDB (1997)it is obvious that the aquifer is not a suitable sole-source water supply to meet the forecasted water demands. The findings of this study reinforce the need to develop alternative water supplies in the study area and to supplement them with water conservation and aquifer protection strategies.

4. Results of climate change impacts in the Edwards BFZ aquifer region: the lumped-parameter ground water model

In this section, the impact of climate change on Edwards BFZ aquifer springflows is assessed by means of a rainfall–runoff model (Reed et al., 1997) linked to a lumped-parameter ground water model (Wanakule and Anaya, 1993; Watkins, 1997). The lumped-parameter ground water model presented in this section was implemented to examine trends of Edwards aquifer response under global warming scenarios produced by alternative GCMs. The GWSIM IV was implemented in Section 3 to examine in refined detail the impacts of global warming (based on scaling factors from a leading GCM, the GFDL R30) under various pumping scenarios. The lumped-parameter model of this section, on the other hand, is implemented to examine broad trends in Edwards aquifer impacts obtained from a variety of GCMs and based on the 1975–1990 historical pumping level.

Historical precipitation and temperature data for the period 1975–1990 obtained from the VEMAP database (Kittel et al., 1997) were used as inputs to the Reed et al. (1997) rainfall–runoff model. After the rainfall–runoff model was calibrated to match 1975–1990 streamflow data (see Martinez, 1998), the impacts of climate change in the Edwards BFZ aquifer were evaluated by means of a two-step procedure. First, $2 \times CO_2$ climate scenarios were generated by applying climate-scaling factors to the VEMAP precipitation and temperature time-series. The scaled precipitation and temperature time series were then input to the rainfall–runoff model to generate the $2 \times CO_2$ streamflows, which, in turn, were used to calculate aquifer recharge that drives ground water processes (recharge was calculate by the method of

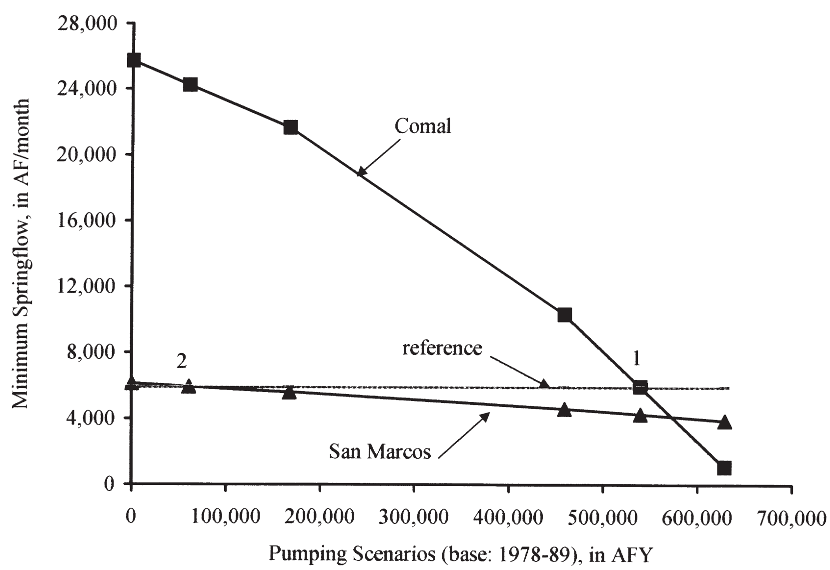

Fig. 8. Minimum Comal and San Marcos springflow as a function of ground water pumping under climate under $2 \times CO_2$ conditions (1978–1989 base period of average recharge; 1 AF = 1233 m^3).

Wanakule and Anaya, 1993). Finally, Edwards BFZ aquifer levels and springflows were simulated under $2 \times CO_2$ conditions with the Watkins (1997) ground water model.

Historical aquifer pumping for the period 1975–1990 served as the direct human-induced aquifer stress. Average annual pumping in the Edwards BFZ aquifer in the period 1975–1990 was 440,500 AFY. The 1975–1990 period had an average annual aquifer recharge of 824,250 AFY, which was slightly above the post-drought (i.e. 1960–1995) average recharge of 800,000 AFY. The climate change scenarios examined in this section can be interpreted as those which would hold for near-average ground water recharge conditions under $2 \times CO_2$ climate and aquifer pumping equal to the 1975–1990 average of 440,500 AFY. Climate change impacts on springflow for a pumping 25% larger than the 1975–1990 historical average are also evaluated in this section.

4.1. Historical climate in the study area

Climate data covering the 99-year period from January 1895 to December 1993 were provided for the study area by VEMAP (Kittel et al., 1997). Average monthly precipitation and temperature data were determined for cells on a $0.5^\circ \times 0.5^\circ$ latitude/longitude grid over the Edwards BFZ region. In order to model climate effects on surface and subsurface water availability, the VEMAP data (given at a $0.5^\circ \times 0.5^\circ$ resolution) were interpolated to a scale compatible with the sizes of the Edwards BFZ aquifer drainage basins. This interpolation is necessary because the ground water simulation program is a lumped parameter model: input data, aquifer properties, and results are all defined on a river basin basis (Martinez, 1998). Precipitation and temperature for each of the nine river basins in the Edwards BFZ aquifer were then input to the rainfall–runoff model to generate streamflow and ground water recharge.

4.2. Rainfall–runoff hydrologic model

Streamflow seepage is the primary source of recharge to the Edwards BFZ aquifer. Streamflow was simulated by means of the rainfall–runoff model developed by Reed et al. (1997). The model predicts streamflows given precipitation, minimum and maximum temperature, and soil water-holding capacity data. An accounting procedure was performed in which rainfall is distributed between soil moisture, runoff, and evaporation. Calibration runs were performed to accurately reproduce a time-series of historical (1975–1990) streamflow measurements reported in Wanakule and Anaya (1993). Recharge to the Edwards BFZ aquifer was calculated as a function of streamflow. The Reed et al. (1997) hydrologic model, therefore, provides the necessary link between climate and ground water.

The rainfall–runoff model performs an accounting procedure for soil moisture within each drainage basin in the Edwards BFZ region. A monthly simulation time step is used by the model. Precipitation (P) is distributed between near-surface soil moisture (w), evapotranspiration (E), and rainfall excess, which eventually becomes streamflow (Q). For each time step "t", the new soil moisture (w_t) is calculated using the following equation:

$$w_t = w_{t-1} + P_t - E_t - Q_t \tag{7}$$

Evapotranspiration (E) and streamflow (Q) are predicted using functions described below.

The temperature-based Hargreaves equation (Shuttleworth, 1993) was used to estimate evaporation in a two-stage approach. First, the potential evapotranspiration rate (E_p) was calculated using the following equation:

$$E_p = 0.0023 S_0 (T_{max} - T_{min})(\bar{T} + 17.8) \tag{8}$$

where E_p is potential evapotranspiration (mm/day), S_0 is the evaporative capacity of the solar radiation flux (expressed in mm/day), T_{max} is the mean maximum temperature (°C), T_{min} is the mean minimum temperature, and $\bar{T}$ is the average temperature for a given month.

Potential evapotranspiration was adjusted by factors which account for non-ideal conditions, such as unsaturated soil and crops other than grass. There are two adjustment factors. The first factor is the crop coefficient (K_c). This factor considers the amount of resistance a particular type of vegetation introduces to restrict transpiration. Vegetation is variable in the Edwards Aquifer region. As a result, K_c is used as a calibration parameter. The second factor is a soil–moisture extraction function (K_s). This factor is also related to vegetation resistance, in that soil moisture controls the amount of water available to plants. The value of K_s is given by

$$K_s = \frac{w}{w^*} \tag{9}$$

where w^* is the soil's water holding capacity. Average soil water-holding capacities in each of the nine Edward BFZ region river basins were obtained from the United States Department of Agriculture (USDA) State Soil Geographic Data Base (STATSGO, USDA, 1991). The complete equation used to predict evapotranspiration is

$$E = K_c K_s E_p \tag{10}$$

The rainfall–runoff model predicts runoff as a function of precipitation and soil moisture. The amount of precipitation (P) which becomes streamflow (Q) is determined by a soil-saturation function α:

$$Q = \alpha P \qquad \text{if } w < w^* \tag{11}$$

where w is soil moisture and w^* is the soil water-holding capacity. The soil-saturation function α is defined by

$$\alpha = \left[\frac{w}{w^*} A^{(1-(w/w^*))} \right] \tag{12}$$

where A is a constant that is used to calibrate the predicted streamflow with observed values. In months when the soil moisture exceeds the infiltration capacity of the soil, the surplus precipitation is assigned as streamflow.

Evaporation scaling to $2 \times CO_2$ conditions was accomplished by scaling temperature, since according to Eq. (8), potential evapotranspiration was expressed as a function of temperature, while the solar flux S_0 was assumed to remain constant (see Loáiciga et al., 1996b). Streamflow scaling to the $2 \times CO_2$ scenario was done by scaling precipitation, due to the relationship between streamflow and precipitation expressed by Eq. (11). The other hydrologic flux that appears in the water balance Eq. (7) is precipitation, which was scaled directly from the scaling ratios for precipitation.

4.3. Lumped-parameter ground water model

The ground water model's stresses are ground water pumping and recharge, and it simulates monthly hydraulic head and springflows (Watkins, 1997). The aquifer system was conceptualized as a series of nine rock-filled "tanks" or "cells" which represent the region's major river drainage basins (shown in Fig. 1). Aquifer parameters are treated as uniform within each cell but varied from cell to cell, thus the name "lumped-parameter" model. The recharge to each cell was calculated using empirical recharge functions that were developed using streamflow seepage analysis (Wanakule and Anaya, 1993, see below). The Watkins' model simulates hydraulic heads and springflows in the Edwards BFZ aquifer based on a set of coupled water-balance equations, one for each river basin of the Edwards BFZ aquifer (the water balance equations are one-dimensional, discretized, versions of the ground water Eq. (3), introduced in relation to the GWSIM IV). Hydraulic properties (i.e. storage coefficient and transmissivity) depend on hydraulic head. This produces a non-linear, time-dependent, system of equations which was solved numerically according to a scheme presented in Watkins (1997). The lumped-parameter ground water model has been calibrated based on water levels at selected observation wells and measured flows at Comal and San Marcos springs.

The recharge functions used by the lumped-parameter model provide a mechanism to simulate the interaction between surface water and groundwater in the study area. Wanakule and Anaya (1993) developed empirical functions to estimate ground water recharge based on recharge ratios (RR) and the upstream (Q_U) and within-drainage basin (Q_I) streamflows. The recharge ratios (RR) are defined as follows:

$$\mathrm{RR} = \frac{\text{Recharge}}{\text{Inflow}} = \frac{Q_U + Q_I - Q_L}{Q_U + Q_I} \tag{13}$$

Q_L in the above equation denotes the streamflow measured at the downstream gauge in a drainage basin. In most cases, the recharge ratios (RR) are non-linear functions of the basins' inflows ($Q_U + Q_I$). In some basins, however, the basins' hydraulic heads are also considered due to the effect on seepage effected by a shallow water table (Wanakule and Anaya, 1993). Once the recharge ratios are calculated, aquifer recharge is estimated by $R = \mathrm{RR}(Q_I + Q_U)$. For example, for the Frio River basin, the recharge equation is as

Table 2
Annual scaling precipitation and temperature factors from several GCMs (scaling factors represent averages over the Edwards BFZ aquifer)

General circulation model (GCM)[a]	Precipitation ($P_{2\times CO_2}/P_{1\times CO_2}$)	Temperature ($T_{2\times CO_2} - T_{1\times CO_2}$) (°C)
CCC	0.943	5.953
GISS	0.931	2.700
GFDL R15 without *Q*-flux	1.152	4.223
GFDL R15 with *Q*-flux	0.990	3.927
OSU	0.959	4.305
UKMO	1.002	3.318
GFDL R30	1.570	3.753

[a] See nomenclature for a description of the full names of the general circulation models.

follows (in which $a = -1.72581$; $b = 4.95753$):

$$R = \left(\frac{\ln(Q_U + Q_I) - b}{a} \right)(Q_U + Q_I) \tag{14}$$

4.4. Climate-change scaling factors

Scaling factors from six GCMs were obtained from the VEMAP Phase I database (Kittel et al., 1995, 1996). Annual precipitation and temperature scaling factors for the six GCMs considered in this section (i.e. the CCC, GISS, GFDL R15 with flux corrections, GFDL R15 without flux corrections, OSU, and UKMO GCMs) are shown in Table 2. Table 2 also includes the annual scaling factors for the GFDL R30 GCM, which was the GCM considered in the simulations of Section 3. It seen that the GFDL R30 GCM produced the largest annual scaling ratio for precipitation. The differences $T_{2\times CO_2} - T_{1\times CO_2}$ from each of the GCM simulations were applied to historical temperature time series, while historical precipitation data were multiplied by the ratios $P_{2\times CO_2}/P_{1\times CO_2}$. The rainfall–runoff and lumped-parameter groundwater models were then implemented using the climate-scaled inputs to drive the simulations.

4.5. Impacts on Comal and San Marcos springflows: 1975–1990 base pumping

The GCM forcing/rainfall–runoff/ground water approach that led to the creation of $2 \times CO_2$ scenarios was describe above. On the other hand, the rainfall runoff and ground water models' outputs obtained using the historical 1975–1990 precipitation and temperature time series (i.e. without scaling) are referred to as the $1 \times CO_2$ results. The range of outcomes from the $1 \times CO_2$ simulations and the $2 \times CO_2$, GCM-based, predictions is shown for Comal springs in Fig. 9. The historically based, or $1 \times CO_2$, predictions constitute the largest simulated Comal springflows shown in that Fig. 9: all the GCMs predicted decreased Comal springflows under the $2 \times CO_2$ climate scenario relative to the $1 \times CO_2$ springflows. Average springflows for Comal springs drop from 14,400 AF/month under $1 \times CO_2$ climate conditions to 8,300 AF/month predicted by the CCC model, which consistently produced the lowest $2 \times CO_2$ Comal springflow values. The GCMs' predictions of Comal springflows in Fig. 9 point to a declining trend of spring discharge as the simulation progressed over time. Predicted springflows by several GCMs fell below the minimum springflow threshold of 100 cfs (5950 AF in a 30-day month) in the summer of 1981, between 1983 and 1987, and after the summer of 1988 until the end of the simulation in 1990.

The range $1 \times CO_2$-simulated and $2 \times CO_2$ GCM-generated springflows at San Marcos springs is shown in Fig. 10. The upper and lower bounds of the range of simulated springflows in Fig. 10 correspond to the $1 \times CO_2$ output and the CCC model, respectively. The range of predictions is very narrow, which is an indication of the low sensitivity of San Marcos springflow to the choice of GCM. No appreciable trend of San Marcos springflow is seen in Fig. 10, although, on average, the CCC-simulated San Marcos springflow was 1400 AF/month lower than the $1 \times CO_2$ values. The 100 cfs (5950 AF/month) minimum discharge was violated by several GCMs repeatedly between 1975 and 1990. All GCM-derived results violated the 100 cfs minimum discharge in 1984 and during 1988–1989.

4.6. Climate change impacts on springflows produced by a 25% pumping increase

The 1975–1990 average pumping of 440,500 AFY was increased 25% to approximate ground water

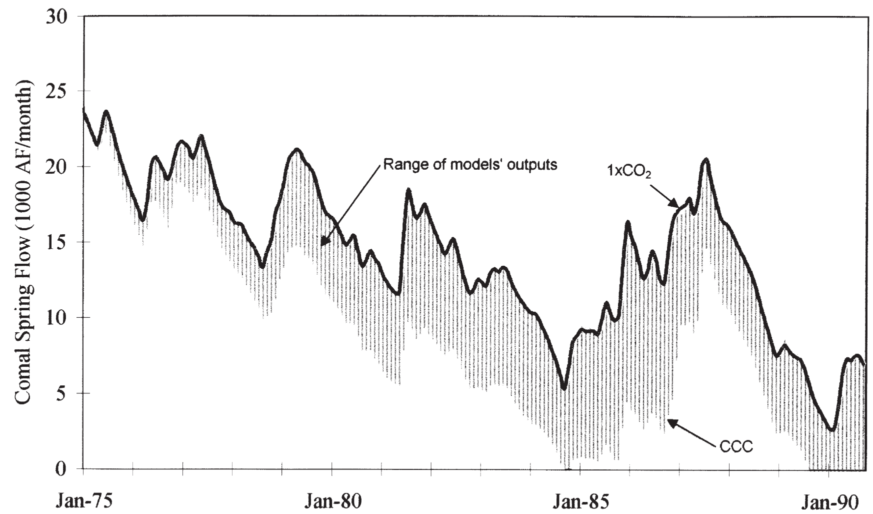

Fig. 9. Range of Comal spring flow predictions from GCMs' scaling factors (1975–1990 base period of above-average recharge; 1 AF = 1233 m^3).

extraction in the Edwards BFZ aquifer predicted to occur around year 2030 (TWDB, 1997). Historical pumping was increased and the groundwater model was run using the climate scaling factors associated with all the GCMs considered in this section. Fig. 11 shows springflows for Comal springs predicted for $2 \times CO_2$ conditions with increased (+25%) pumping. All the simulated values were between the $1 \times CO_2$ (highest) and the CCC GCM (lowest) outputs. It is seen in Fig. 11 that the average springflow drops from 14,500 AF/month to 10,000 AF/month—a decline of 31%—due to the 25% increase in pumping. The declining trend in Comal springflow over time is very noticeable in Fig. 11. The severe-impact springflow level of 100 cfs (=5950 AF/month) is violated very frequently after 1980.

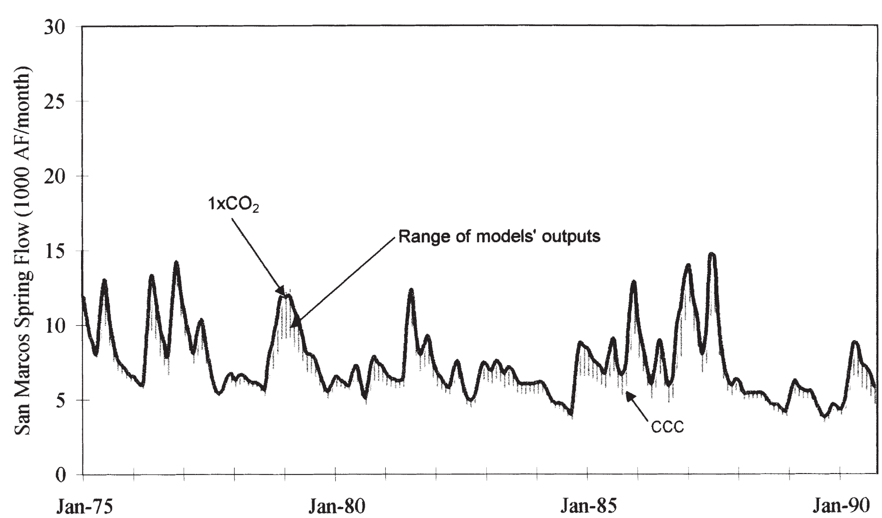

Fig. 10. Range of San Marcos spring flow predictions from six GCMs' scaling factors (1975–1990 base period of above-average recharge; 1 AF = 1233 m^3).

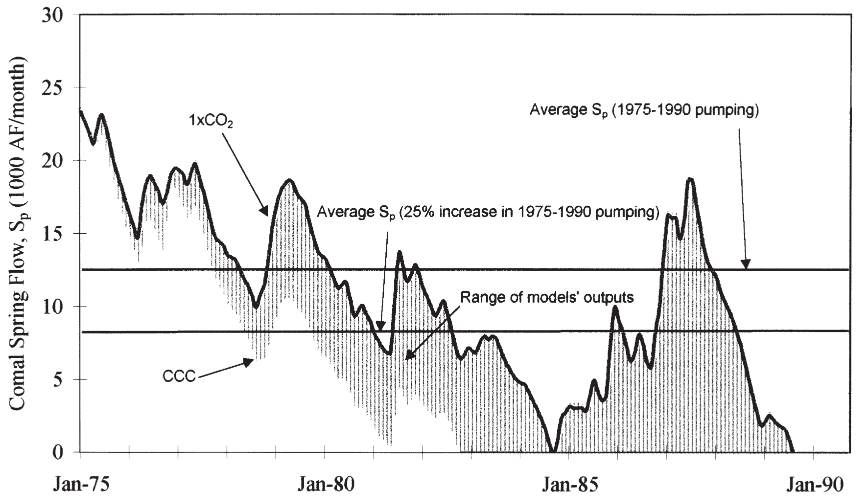

Fig. 11. Range of Comal spring flow predictions under $2 \times CO_2$ conditions and 25% increase in pumping (1975–1990 base period of above-average recharge; 1 AF = 1233 m^3).

The range of impacts caused by a 25% increase in pumping on San Marcos springflow under $2 \times CO_2$ conditions is shown in Fig. 12. Unlike the springflow at Comal springs, the San Marcos springflow remains relatively steady around an average level of 5800 AF/month during the simulation period. This average is lower than the 7400 AF/month springflow associated with historical 1975–1990 pumping. The 5800 AF/month average springflow associated with increased pumping is slightly below the 100 cfs (=5950 AF/month) severe-impact threshold. As it turns out, increased pumping on the order of 25% induces violations of minimum springflow about 50% of the time at San Marcos springs. In summary, the simulation results presented in this section, derived with a base period of above-average aquifer recharge, 1975–1990, suggest that predicted increases in pumping would most likely have a substantial negative impact on the water resources of the Edwards BFZ aquifer under $2 \times CO_2$.

5. Conclusions

Historical climate time series in base periods of extreme water shortage (1947–1959), near-average recharge (1978–1989), and above-average recharge (1975–1990) were scaled to $2 \times CO_2$ conditions to create several aquifer recharge scenarios in a warmer climate. Various pumping scenarios were combined with the $2 \times CO_2$ climate scenario to assess the sensitivity of water resources impacts to climate change in the Edwards BFZ aquifer.

Aquifer simulations carried out with the Edwards BFZ aquifer ground water model (base periods 1947–1959 and 1978–1989) indicate that the Edwards BFZ aquifer is very vulnerable to global warming trends given the existing ground water use and the predicted growth in the study area. It was determined that a level of pumping of 400,000 AFY under "average" $2 \times CO_2$ recharge conditions would preserve discharge at key springs above the severe-impact level of 100 cfs most of the time. However, the TWDB's predicted year 2050 pumping of 636,000 AFY would dry up Comal springs and impose frequent and severe water shortages at San Marcos springs. During drought conditions in a $2 \times CO_2$ climate, a maximum pumping of 140,000 AFY would minimize aquifer impacts while providing a base level of water supply. However, under drought conditions there is no pumping strategy that could prevent discharge shortages at San Marcos and Comal springs.

Aquifer simulations with a lumped-parameter ground water model driven by climate-scaling factors from six GCMs indicate declining springflows at key springs in the Edwards BFZ aquifer relative to the

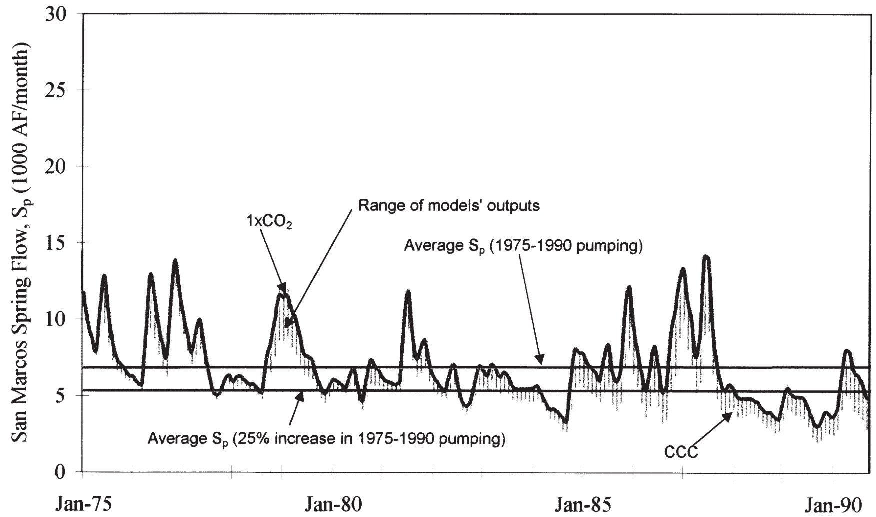

Fig. 12. Range of San Marcos spring flow predictions under $2 \times CO_2$ conditions and 25% increase in pumping (1975–1990 base period of above-average recharge; 1 AF = 1233 m^3).

pattern of springflows obtained under 1975–1990 above-average recharge conditions. The historical patterns in springflows in the period 1975–1990 had negative environmental impacts and led to intense competition for the ground water resources of the Edwards BFZ aquifer. The $2 \times CO_2$ simulations indicate that water shortages and negative environmental impacts associated with declining springflows are likely to be intensified in the Edwards BFZ aquifer if pumping were to remain at the 1975–1990 pumping level of about 440,000 AFY. A set of simulations in which the 1975–1990 average pumping was increased by 25% to 550,000 AFY (a level of average pumping in the Edwards BFZ aquifer predicted to occur around year 2030) have shown more pronounced environmental impacts relative to those caused by a pumping rate of 440,000 AFY.

In summary, with predicted growth and water demand in the Edwards BFZ aquifer region, the aquifer's ground water resources are threatened under $2 \times CO_2$ climate scenarios. Our simulations indicate that $2 \times CO_2$ climatic conditions are likely to exacerbate negative impacts and water shortages in the Edwards BFZ aquifer unless ground water withdrawal is carefully adjusted to changes in ground water recharge conditions.

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References

Campbell, L., 1995. Endangered and threatened species animals of Texas, Texas Parks and Wildlife Department, Austin, Texas, 129pp.

Edwards Aquifer Authority, 1996. Edwards aquifer hydrogeologic report for 1995, Report 96-04, San Antonio, Texas, p. 59 plus appendices.

Garza, S., 1966. Ground water resources of the San Antonio area, Texas: a progress report on studies, 1960–1964, Texas Water Development Board Report 34, Austin, TX, 31pp.

Gleick, P.H., 1989. Climate change, hydrology, and water resources. Rev. Geophys. 27 (3), 329–344.

Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K., 1995. Climate Change 1995: The Science of Climate Change, Cambridge University Press, Cambridge.

Kittel, T.G.F., Rosenbloom, N.A., Painter, T.H., Schimel, D.S., 1995. VEMAP modeling participants, the VEMAP integrated database for modeling United States cosystem/vegetation sensitivity to climate change. J. Biogeogr. 22, 857–862.

Kittel, T.G.F., Rosenblum, N.A., Painter, T.H., Schimel, D.S., Fisher, H.H., Grimsdell, A., 1996. VEMAP participants, The VEMAP Phase I database: an integrated input dataset for ecosystem and vegetation modeling for the conterminous United States, CDROM and [Internet, www], address: http://www.cgd.ucar.edu/vemap.

Kittel, T.G.F., Royle, J.A., Daly, C., Rosenbloom, N.A., Gibson, W.P., Fisher, H.H., Schimel, D.S., Berliner, L.M., 1997. VEMAP2 Participants, A gridded historical (1895–1993) bioclimate dataset for the conterminous United States. Proceedings of the 10th Conference on Applied Climatology, American Meteorological Society, Reno, Nevada.

Klemt, W.B., Knowles, T.R., Elder, G.R., Shieh, T.W., 1979. Ground water resources and model applications for the Edwards (Balcones Fault Zone) aquifer in the San Antonio region, Texas, Texas Department of Water Resources Report No. 239, 88pp.

Knowles, T., 1983. Ground Water Simulation Program—GWSIM IV: Program Documentation and User's Guide, Texas Department of Water Resources, Austin, TX.

LBG-Guyton and Associates, 1995. Edwards/Glen Rose hydrologic communication, San Antonio, Region, Texas, Edwards Underground Water District Report 95-03, p. 38 plus appendices, Austin, TX.

Lettenmaier, D.P., Gan, Y.T., 1990. Hydrologic sensitivities of the Sacramento–San Joaquin river basin, California, to global warming. Water Resour. Res. 26 (1), 69–86.

Loáiciga, H.A., Maidment, D.R., Valdes, J.B., Roos, M., Wood, E.F., 1996a. Report of the Case Study Selection Team, ASCE/USEPA Climate Change Cooperative Agreement, ASCE, Reston, VA, 17pp. plus appendix.

Loáiciga, H.A., Valdes, J.B., Vogel, R., Garvey, J., Schwarz, H.H., 1996b. Global warming and the hydrologic cycle. J. Hydrol. 174 (1–2), 83–128.

Longley, G., 1981. The Edwards aquifer: earth's most diverse ground water ecosystem. Int. J. Speleol. 11, 123–128.

Manabe, S., Wetherald, R.T., 1987. Large-scale changes in soil wetness induced by increase in carbon dioxide. J. Atmos. Sci. 44, 1211–1235.

Maclay, R.W., Small, T.W., 1984. Carbonate geology and hydrology of the Edwards aquifer, San Antonio area, Texas, US Geological Survey Open File Report 83-537, 72pp.

Maclay, R.W., Land, L.F., 1987. Simulation of flow in the Edwards aquifer, San Antonio region, Texas, and refinement of storage and flow concepts, USGS Open File Report 86-532, 86pp.

Martinez, K., 1998. Implementation of a lumped-parameter ground water model to the study of climate change impacts in the Edwards aquifer, Texas, Master of Science thesis, Department of Civil Engineering, University of Texas, Austin.

McKinney, D.C., Sharp, J.M., 1995. Springflow augmentation of Comal Springs and San Marcos Springs, Texas: Phase I—feasibility study, Technical Report 247, Center for Research in Water Resources, University of Texas, Austin, TX.

North, G.R., Bomar, G., Griffiths, J., Norwine, J., Valdes, J.B., 1995. The changing climate of Texas. In: North, G.R., Schmandt, J., Clarkson, J. (Eds.). The Impact of Global Warming on Texas, The University of Texas Press, Austin, TX, pp. 24–49.

Panagoulia, D., 1992. Impacts of GISS-modeled climate changes in catchment hydrology. Hydrol. Sci. J. 37 (2), 141–163.

Prickett, T.A., Lonquist, C.G., 1971. Selected digital computer techniques for ground water resource evaluation, Illinois State Water Survey Bulletin 55, Urbana, Illinois, 62pp.

Puente, C., 1978. A method of estimating natural recharge to the Edwards aquifer in the San Antonio area, Texas, USGS Water Resources Investigations Report No. 78-10, 34pp.

Reed, S.M., Maidment, D.R., Patoux, J., 1997. Spatial water balance of Texas, Center for Research in Water Resources Online Report 97-1 [Internet, www], address: http://www.ce.utexas.edu/prof/maidment/gishyd97/library/wbtexas/wbtexas.htm.

Rose, P.R., 1972. Edwards group, surface and subsurface, Central Texas, Bureau of Economy Geology Report of Investigations No. 74, University of Texas, Austin, 198pp.

Rosenbloom, N., Kittel, T.G.F., 1996. A user's guide to the VEMAP phase I database, NCAR/TN-431, 53pp.

Shuttleworth, W.J., 1993. Evaporation. In: Maidment, D.R. (Ed.). Handbook of Hydrology, McGraw-Hill, New York chap. 4, pp. 18, 30–31.

Texas Water Development Board, 1997. Water for Texas: A Consensus-Based Update to the State Water Plan, Volume II, Technical Planning Appendix, Document GP-6-2, p. 343 plus appendix, Austin, TX.

Thorkildsen, D., McElhaney, P.D., 1992. Model refinement and applications for the Edwards BFZ aquifer in the San Antonio Region, Texas Water Development Board Report 340, Austin, Texas, 33pp.

United States Department of Agriculture, 1991. State Soil Geographic Data Base (STATSGO)—Data user's guide, Miscellaneous Publication No. 1492, Washington, DC.

United States Fish and Wildlife Service, 1996. San Marcos and Comal Springs and Associated Ecosystems (Revised) Recovery Plan, USFWS Austin Ecological Services Station, Austin, TX, 120pp.

Wanakule, N., Anaya, R., 1993. A lumped parameter model for the Edwards Aquifer, Technical Report No. 163, Texas Water Resources Institute, Texas A and M University, College Station Texas, 83pp.

Watkins, D.W., Jr., 1997. Optimization techniques for the planning and management of robust water resources systems, PhD dissertation, University of Texas, Austin, Texas.