

# Travel Times Along Selected Flow Paths of the Edwards Aquifer, Central Texas

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## Abstract

Flow path travel times in the structurally controlled, karstic Edwards aquifer were estimated using simulated ground-water levels obtained from a finite-element model. For this analysis, simulated monthly ground-water levels were averaged over an 11-year calibration period to minimize the transient effect of short-term recharge and discharge events. The 1978-89 calibration period was characterized by average to wetter-than-average climatic conditions; simulated water-level and spring-flow compared favorably with measured data. Flow paths for which travel times were estimated range from 1,250 to 10,000 feet wide and from about 8 to 180 miles long. Effective aquifer thickness and effective porosity can be highly variable and is poorly defined throughout most of the aquifer. Accordingly, travel-time estimates were computed within known or inferred thicknesses and porosities within known or inferred ranges of 350 to 850 feet and 15 to 35 percent, respectively. The minimum rock matrix porosity for each element was divided by 10 to estimate a minimum time of travel (a worst case time of travel). Travel times range from 14 to 160 years for a flow path from the Blanco River Basin to San Marcos Springs and from 350 to 4,300 years for a flow path from the West Nueces River Basin to Comal Springs. Travel times near the minimum of the ranges are similar in magnitude to those determined from tritium isotopes in spring water, thus supporting the hypothesis that effective porosity and effective thickness of the aquifer is less than the respective ranges.

## INTRODUCTION

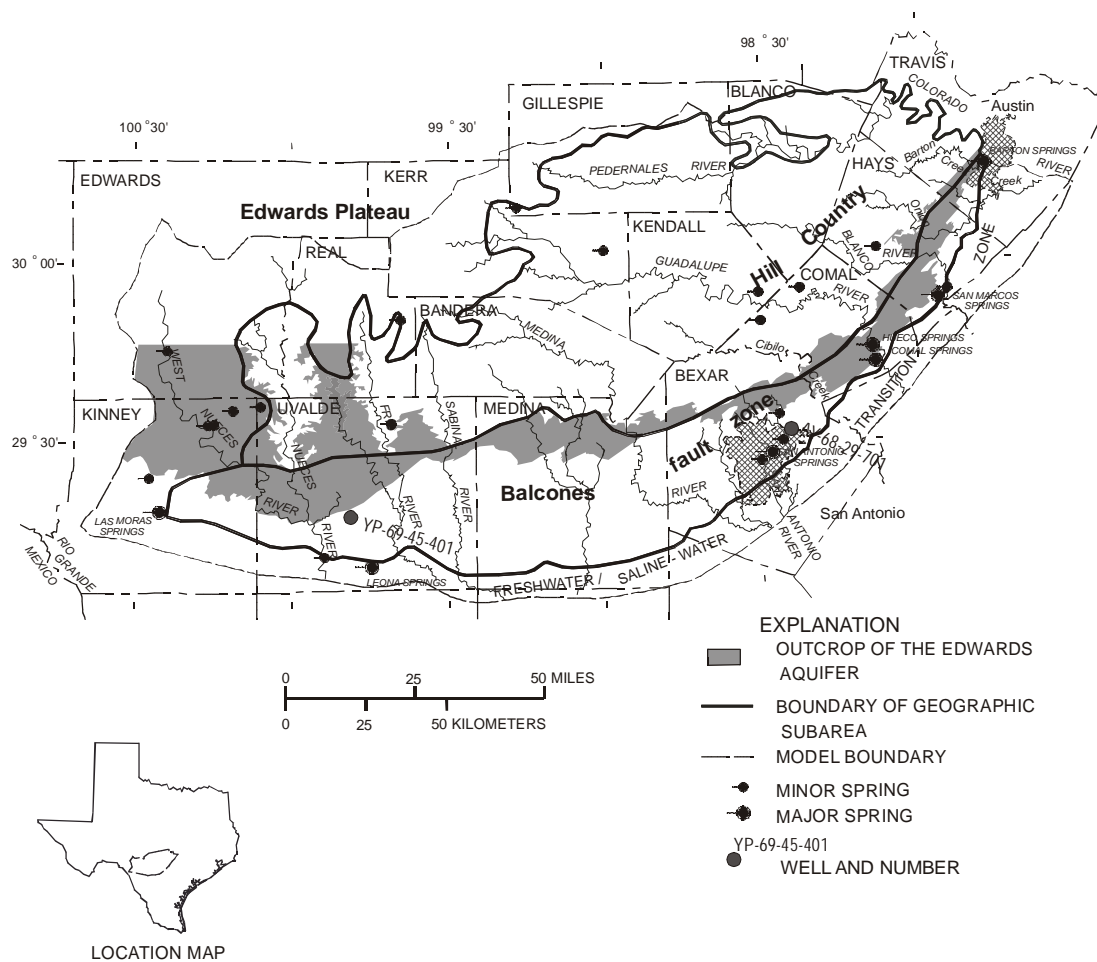
The structurally controlled, karstic Edwards aquifer is the sole source water supply for San Antonio, Texas. Water enters the Edwards aquifer from precipitation over its outcrop area and streamflow from the catchment area of the Hill Country. The gaining streams incised into the Trinity aquifer in the Hill Country cross the outcrop of the highly permeable and fractured rocks of the Edwards aquifer in the Balcones fault zone and disappear underground (fig. 1, Kuniansky, 1989). The major natural discharge from the Edwards aquifer is at springs. Two of the major springs, Comal and San Marcos are habitat for endangered species. This karst system is unique due to its existence in a semi-arid area and the geologic structure that controls the direction of ground-water movement in the aquifer. A finite-element model of the Edwards and Trinity aquifers within the Hill Country and Balcones fault zone in central Texas (fig. 1) (Kuniansky, 1994, 1995; Kuniansky and Ardis, [in press]) was designed to incorporate the geologic and hydrologic conditions affecting ground-water flow and to better understand the flow system. Faulting throughout the study area, and particularly in the Balcones fault zone, results in horizontal anisotropy that strongly influences regional ground-water flow patterns. The finite-element method is one of the few numerical methods that can represent hydraulic characteristics that vary in the horizontal direction and was well suited for developing a heterogeneous

continuum model of this karst system. A detailed deterministic numerical model synthesizes known information including geologic structure, recharge and discharge, and ground-water level by solving the ground-water flow equations for water levels given boundary conditions, parameters (hydraulic properties), and stresses (pumping and recharge).

The purpose of this extended abstract is: to describe the geologic structure that affects ground-water flow direction within the Edwards aquifer; to describe how flow paths were determined from the average simulated potentiometric surface (1978-89); to show flow paths from points where water enters the aquifer at streams to major natural discharge features (Comal or San Marcos Springs); and to provide worse-case (fastest) estimated times of travel along these flow paths. The model design, layering, and boundary conditions are published in Kuniansky, 1994 and 1995, and are not described herein.

## Description of the Study Area

The Hill Country is characterized by rough rolling terrain dissected by the headwaters of the streams within the Nueces and Guadalupe River Basins. These streams have been eroding headward into the Edwards Plateau forming narrow valleys with steep carbonate walls. Wider stream valleys along the major streams may have formed by lateral cutting and karstic processes during periods of greater rainfall (Wermund and others, 1974).



**Figure 1.** Location of study area.

The Balcones fault zone is characterized by a series of en echelon faults that trend southwest to northeast along the length of the region (fig. 2). The terrain within the Balcones fault zone is much less rugged than the Hill Country. Gently rolling hills and wide alluvial valleys are typical near the southeastern border of the fault zone. Surface karst features of karren [surface grooves ranging in width from a few inches to 5 feet (ft)] and tinajitas (dissolved pools in streambeds or formed by springs) are commonly found in and along streams. Shallow sinkholes and swallow holes also are fairly common.

Major rivers within the study area include the Nueces, Frio, Sabinal, Medina, Guadalupe, Blanco, Pedernales and Colorado Rivers all of which incise the Edwards and Trinity aquifers. Within the Hill Country, the majority of the streams are gaining streams. Within the Balcones fault zone, many streams become intermittent because of losses to the Edwards aquifer. Streamflow losses and percolation of rainwater account for the majority of recharge to the Edwards aquifer along its outcrop.

The climate is classified as subhumid, subtropical in the eastern part of the study area and semiarid in the western part. Mean annual rainfall ranges from 32 inches per year (in/yr) in the east to 20 in/yr in the west (1951-80). There are two rainy seasons, spring and fall. Rainfall varies greatly from year to year, but long-term seasonal averages indicate that winter is the driest season. Mean annual temperature is 69 degrees Fahrenheit (Riggio and others, 1987).

Over most semiarid regions of the Edwards Plateau and Hill Country, soil development is poor and generally less than 1 ft thick. In the Edwards Plateau, soils tend to be calcareous stony clays vegetated by desert shrubs in the west and juniper, oak, and mesquite in the east. The Hill Country soils and vegetation are similar to those of the Edwards Plateau. In the northeastern part of the Balcones fault zone, soils are calcareous clay, clayey loam, and sandy loam with some prairie vegetation. West of San Antonio in the southwestern part of the Balcones fault zone, vegetation is predominantly juniper, oak and mesquite (Kier and others, 1977).

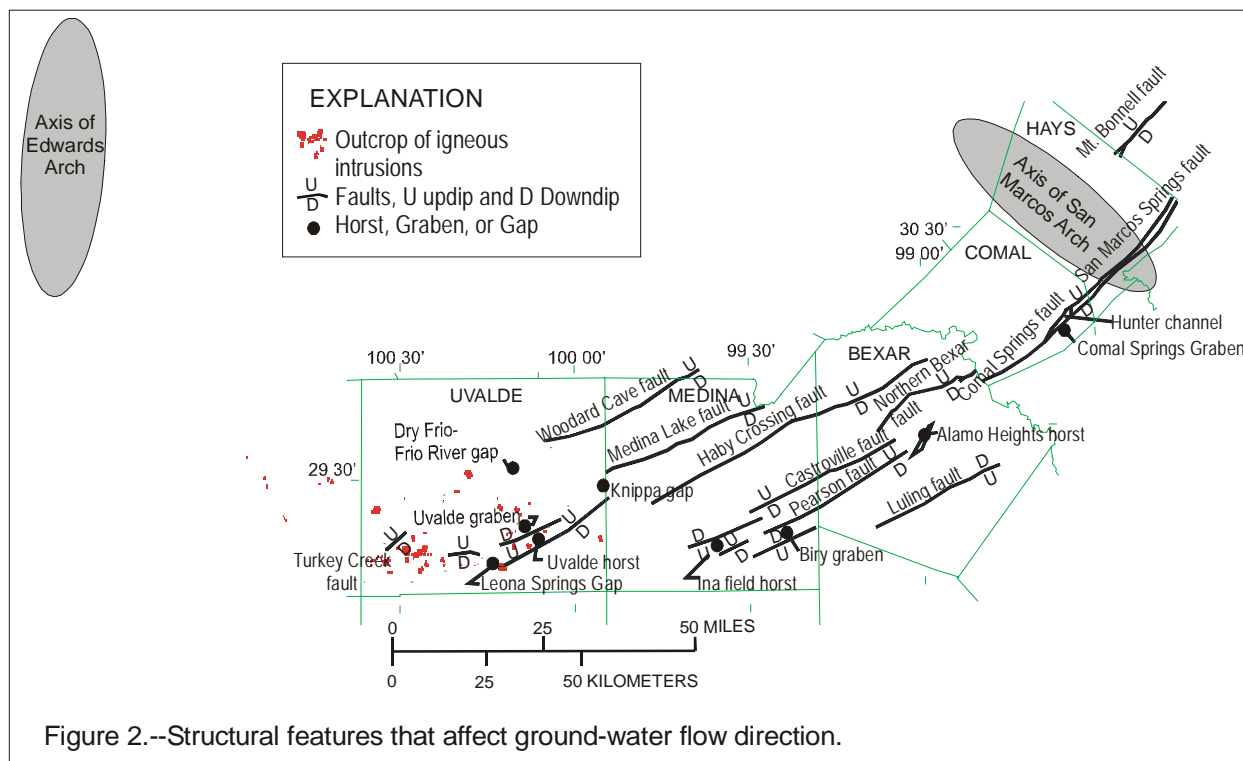


Figure 2.--Structural features that affect ground-water flow direction.

The major aquifers are the Trinity in the Hill Country and the Edwards in the Balcones fault zone. All rock units are of Cretaceous age (Barker and other, 1995; Barker and Ardis, 1996). The Trinity aquifer is composed of dolomitic limestone with interbeds of sand, shale, and clay. The Lower Glen Rose Limestone and the Hensel Sand are the most productive units of the Trinity aquifer. The Upper Glen Rose has been eroded, exposing rocks of the Lower Glen Rose along the Blanco, Guadalupe, and Medina Rivers and Cibolo Creek. The Hensel Sand is exposed along the Pedernales River (Ashworth, 1983). Rocks of the Edwards aquifer (the Edwards Group) have been mostly eroded and cap a few hills in the eastern part of the Hill Country.

The Lower Glen Rose is cavernous in the area of Cibolo Creek (Wermund and others, 1978). Near the confluence of the Pedernales and Colorado Rivers at the northeastern limit of the Hill Country, the lower part of the Trinity aquifer is exposed along the streams. In this area, the most productive units of the Trinity aquifer are the Hosston and Sligo Formations.

The Edwards aquifer is unconfined in a narrow strip where rocks of the aquifer crop out along the southern edge of the Hill Country and the Edwards Plateau. Most of the Edwards aquifer is confined down-dip of the outcrop. Rocks that compose the Edwards aquifer tend to be honeycombed, horizontally bedded, and more permeable than rocks of the adjacent Trinity aquifer. Dissolution of rocks that parallel faults and joints has

resulted in large secondary permeability. Numerous caves have been mapped within the study area (Wermund and others, 1978).

## STRUCTURAL CONTROLS ON GROUND-WATER FLOW

Faults and structural lineaments have been mapped extensively in the Hill Country and Balcones fault zone. Locations of major faults within the Hill Country and Balcones fault zone are shown in figure 2 along with the location of positive anticlinal features in the pre-Cretaceous surface and the outcrop of igneous intrusions.

Faults, joints, and dissolution of the rocks has greatly affected the ground-water flow system. In part, this is a result of the depositional and diagenetic character of the carbonate bedrock (Barker and Ardis, 1996). The limestone and dolomite of the Edwards-Trinity is not pure containing clay, shale, and sand. Diagenetic alteration of burrowed limestone beds has resulted in the development of vuggy porosity. The burrowed limestone bedrock members of the Edwards-Trinity aquifer are not the most permeable part of the aquifer system. Solution caverns formed along joints and faults represent the zones of greatest permeability. Fault and fracture zones within the Balcones fault zone created an avenue for meteoric water to percolate through the carbonate rocks. Along with the faulting, joints parallel and perpendicular to the fault system provide an opportunity for the movement of ground water. As streams incised bedrock in the Hill Country

and Balcones fault zone, the development of spring flow further increased the dissolution of rock. Over geologic time, dissolution of carbonate rock developed into a system of caverns and dissolution channels. More caverns formed in the Edwards aquifer, in the Balcones fault zone, than in the Hill Country. These caverns tend to be linear and parallel to the faults or joints (Fieseler, 1978, fig. 4; Wermund and others, 1978, fig. 12; Woodruff and others, 1989, figs 6 and 14; Veni, 1988 p. 12-13). Many caves parallel faults, with some aligned with joints perpendicular to the faults. Veni (1988, p. 13) hypothesized that tensional joints corresponding with many of the en echelon faults, provided preferential ground-water flow paths for the development of caverns and preceded the fault movement.

En echelon normal fault movement has resulted in a series of horst and graben structures. Many of the fault structures form barriers restricting or diverting the lateral movement of ground water. Grabens form flow conduits in the Edwards aquifer (fig. 2, Maclay and Land, 1988).

Two important barrier faults are present along the central part of the Haby Crossing and Pearson faults; here the Edwards aquifer is completely displaced. Other barrier faults include Woodard Cave, Turkey Creek, Medina Lake, Castroville, Northern Bexar, Luling, Comal Springs, San Marcos Springs, and Mount Bonell (Maclay and Small, 1984; Maclay and Land, 1988). In areas where rocks of the Edwards aquifer crop out, erosion and upthrown horst structures have combined to help reduce the saturated thickness of the Edwards aquifer. In the confined part of the system, horst structures have juxtaposed less permeable Trinity rocks with the more permeable rocks of the Edwards aquifer. Important horst structures include Uvalde, Ina Field, and Alamo Heights (Maclay and Land, 1988). The Woodard Cave and Mount Bonell faults mark the southeastern boundary of major blocks of the Edwards aquifer, juxtaposing the Trinity aquifer to the northwest with the Edwards aquifer to the southeast (Small, 1986).

The horst and graben structures may combine to divert ground-water flow. The Uvalde graben lies north of the Uvalde horst. Ground water that would normally flow downgradient is obstructed horizontally by the horst structure and thus moves parallel to the horst within the dropped block of the Uvalde graben. The Comal Springs graben, bounded by the Comal Springs fault on the northwest and a series of upthrown blocks to the south, is a narrow area of highly transmissive rocks. The Hunter channel (fig. 2), between Comal and San Marcos Springs, contains highly transmissive rocks.

A series of gaps have formed in areas where minor fault displacement has occurred; the diversion of

ground-water flow in these areas is less common. Major gaps include the Dry Frio-Frio River, Leona Springs, and Knippa gaps (fig. 2).

The San Marcos arch is a pre-Cretaceous positive anticlinal feature (fig. 2). The Edwards-Trinity aquifer is thinner over the San Marcos arch (Ashworth, 1983, fig. 7). Localized highs in the pre-Cretaceous base of the aquifer system can reduce the saturated thickness of the more permeable Cretaceous rocks (Barker and Ardis, 1992; Ardis and Barker, 1993) restricting regional ground-water movement. The San Marcos arch has been associated with a ground-water divide in the Edwards aquifer often used as a no-flow boundary for local model studies of the Edwards aquifer (Klemt and others, 1979; Maclay and Land, 1988; Slade and others, 1985). The Edwards Arch is another positive anticlinal feature formed in the pre-Cretaceous surface that resulted in less deposition of lower Trinity rocks near the apex of the arch. The apex of this arch occurs within Edwards County along a south-southwest to north-northeast axis.

Basaltic igneous rocks occur in Uvalde and Medina Counties (fig. 2) and intrude overlying Cretaceous rocks, locally affecting ground-water flow. Although, the subsurface extent of these intrusions are not known, they may impede lateral movement of ground water. Calibration to observed ground-water levels in Uvalde County was improved when the intrusions were simulated as localized areas of reduced transmissivity.

## **TRAVEL TIMES ALONG SELECTED FLOW PATHS**

Travel times were estimated along flow paths in the Edwards aquifer using simulated ground-water levels. For this analysis, simulated monthly water levels were averaged over an 11-year calibration period (1979-89) to reduce the transient effects of short-term recharge and discharge events. The 1978-89 period was characterized by average to wetter-than-average climatic conditions.

The finite-element, transient flow model of the Edwards aquifer was calibrated to 10 water-level hydrographs, the major and minor springs, and base flows of continuously gaged streams (not shown). The hydrographs shown in fig. 3 show the best and worst fits of the simulation. Simulated water levels at well YP-69-45-401, in Uvalde County, range from approximately 5 to 90 ft too high (worst fit). The well in Bexar County, AY-68-29-701, near the index

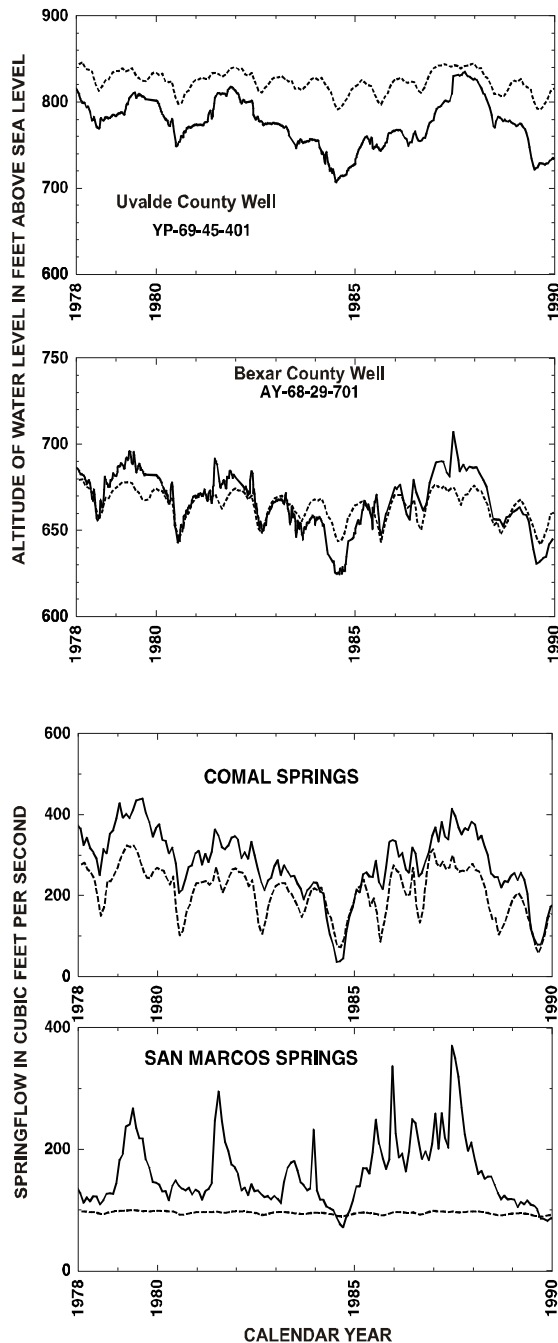


Figure 3.-- Observed (solid line) and simulated (dashed line) ground-water levels and springflow.

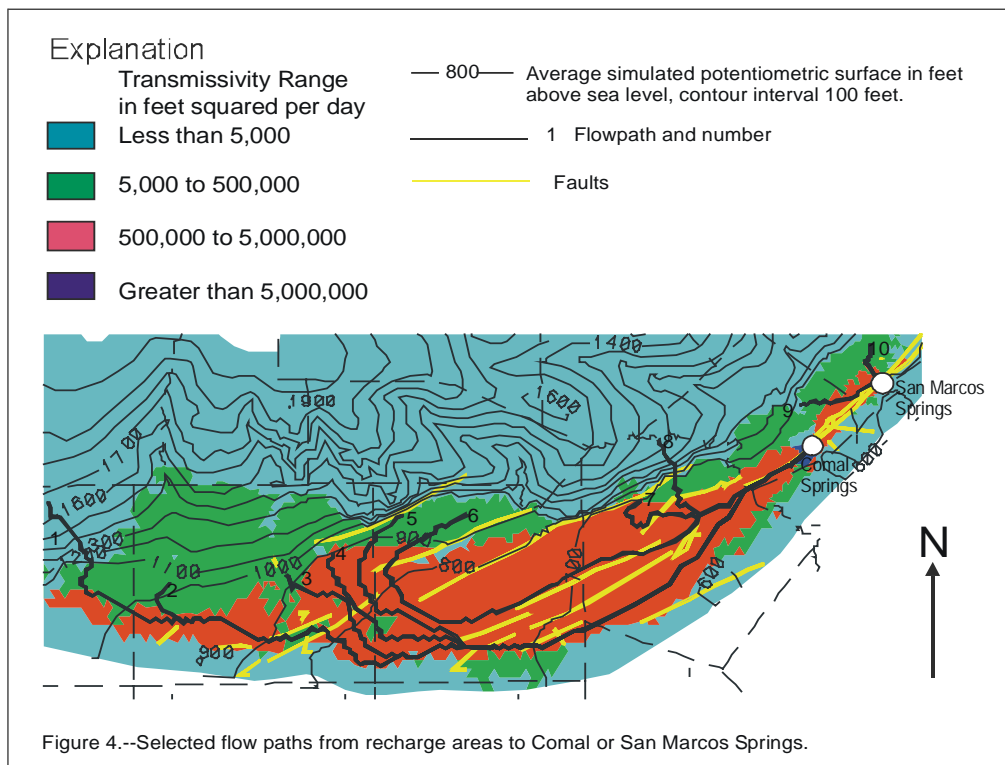
well (also known as, J-17) for Comal springs and simulated water levels match observed levels much of the time to a maximum error of approximately 35 ft. The simulated water level is too high in the west (YP-69-45-401 in fig. 3), which means that the simulated gradient is steeper than the actual gradient. A steeper gradient results in faster velocity and travel-time estimates.

Comal Springs matches some of the time, but is simulated with the worst error approximately 110 cubic feet per second less flow than observed springflow. The local recharge at San Marcos Springs was not included in recharge estimates for the model, thus only the base springflow was matched (fig. 3). The effect on travel times of underestimating the springflow is slower estimated velocity and travel times.

The method for estimating times of travel is straightforward. Simulated Darcy flux vectors are calculated for each element of the finite-element model using the average head value for 1978-89 at each node to compute the local gradient for each element (Kuniansky, 1990). The local coordinate system is oriented in the direction of anisotropy, such that all cross products of the transmissivity tensor are zero, thus only the maximum and minimum transmissivity,  $T_{xx}$  and  $T_{yy}$ , respectively, are non-zero. The gradient in the local coordinate system ( $\delta h/\delta x$  and  $\delta h/\delta y$ ) is multiplied times  $T_{xx}$  and  $T_{yy}$  to compute the Darcy flux ( $\text{ft}^2/\text{day}$ ) in the local x and y directions. The local flux vectors are then converted to the global coordinate system using the angle of the anisotropy (Kuniansky, 1990). The transmissivity ranges shown on figure 4 are  $T_{xx}$ , the maximum transmissivity. In the areas with faults (fig. 4), the angle of anisotropy is along the strike of the faults shown. In areas with no major faults or gaps (fig. 2), the aquifer is simulated as isotropic. Dividing the flux vector by aquifer thickness (ft) and porosity (dimensionless) provides an estimate of the advective velocity of a particle of water for that element. Porosity and thickness data (not shown) were obtained from published maps by Hovorka and others (1993).

Flow paths were selected manually by plotting the flow vectors computed from the average simulated potentiometric surface (fig. 4), selecting a starting point, and following the flow vector to an adjacent element until the endpoint (Comal or San Marcos Springs) was reached. The average velocity and distance between elements is computed from the two adjacent elements (fig. 5). The time of travel from one element to the next is computed by dividing the distance by the velocity and summed up along the flow path. In general, the flow paths support much of the work on the conceptual framework of the Edwards aquifer described by Maclay and Small, 1984; Maclay and Land, 1988; and Groschen, 1996.

Flow paths for which travel times were estimated range from 1,250 to 10,000 feet wide and from about 8 to 180 miles long. Effective aquifer thickness and effective porosity can be highly variable and is not well defined throughout most of the aquifer.



Estimates of travel times were computed from aquifer thickness and rock matrix porosities within known or inferred ranges of 350 to 850 ft and 15 to 35 percent, respectively (table 1). Computations involving total aquifer thickness and maximum rock matrix porosity yield maximum travel times. In a karst system, such as the Edwards, the entire thickness of the aquifer may not be the permeable or transmissive zone. Additionally, the rock matrix porosity may not be representative of the effective porosity (connected void spaces). For example, Small and Maclay (1982) report porosity of less than 3 percent for parts of the Edwards aquifer; Sieh (1975) report porosity of less than 1 percent for parts of the Edwards aquifer; Hovorka and others (1993) report effective porosities as low as 5 percent. The minimum rock matrix porosity for each element (range along flow path, tab. 1) were divided by 10 to estimate a minimum time of travel. Travel times range from 14 to 160 years for a flow path from the Blanco River Basin to San Marcos Springs and from 350 to 4,300 years for a flow path from the West Nueces River Basin to Comal Springs. Minimum travel-time estimates are similar in magnitude to the estimates of the age of the water at these springs determined from tritium isotopes in water (Pearson and Rettman, 1976; Pearson and others, 1975). This supports the hypothesis that effective porosity and effective thickness of the aquifer is probably less than its respective range (tab. 1).

Various authors used the tritium data of Pearson and Rettman (1976) to interpret ages for the waters of the Edwards aquifer. Campana and Mahin (1985) used a discrete state compartment model to describe the observed tritium concentrations. This model assumes that water moves from one cell to another as a discrete unit, then mixes completely with water within that cell. Calculated ages were determined as 47 to 132 years from Uvalde County, 57 to 123 years from Medina County, and 38 to 123 years from Bexar County. The estimated age of water was 91 years from Comal Springs, and 16 years from San Marcos springs. More recently, Shevenell (1990) used two hydrologic models, well-mixed and piston flow, to describe the observed tritium concentrations. These two end-member hydrologic models allow determination of interpreted minimum and maximum age dates for observed tritium concentrations. The well-mixed model indicated water from Uvalde County as 96 to 187 years old, Comal Springs water 318 to 521 years old and San Marcos Springs water 61 to 75 years old. The piston-flow model indicated Uvalde County water was 12.5 to 17.9 years old, Comal Springs water was 14.5 to 17.5 years old, and San Marcos Springs water was 10.5 to 15 years old.

The estimated dates obtained from the well-mixed model (Shevenell, 1990) agree more closely with the numerical model than the other hydrogeochemical models. In general, both the numerical model estimates and the geochemical models indicate that the waters obtained from Comal Springs are a mixture of older waters than those obtained from San Marcos Springs.

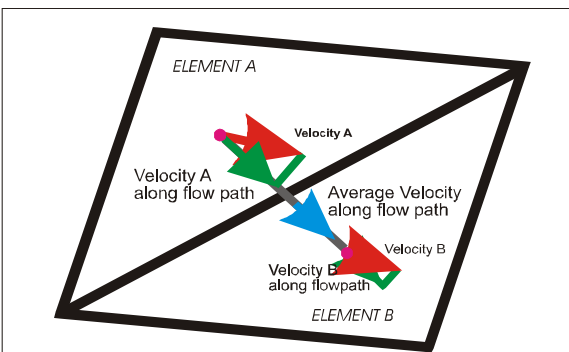


Figure 5.-- Diagram of average velocity calculated between two elements.

### Limitations of the Model and Flow Path Analysis

In developing a numerical model of an aquifer system, many simplifications of the system are required in order to approximate it mathematically. In this quasi three-dimensional finite-element model, ground-water flow is simulated as horizontal and two-dimensional within two model layers, with vertical leakage occurring between layers. The ground-water flow equation solved by the numerical model is the continuity equation for flow with the incorporation of Darcy's law, derived from the principals of conservation of mass and energy along with the assumptions that water is incompressible and of constant viscosity. Mathematically, this is a boundary-value partial-differential equation that is solved numerically. The partial-differential equation is solved for aquifer head, given boundary conditions of specified head, specified flux, or head-dependent flux and aquifer parameters and stresses. The equation is valid for ground-water flow problems when the velocity of ground water is slow and laminar. In karst terranes, it is possible for flow through caverns and dissolution channels to be turbulent. Thus, the equation is not valid for the entire flow domain of the Edwards and Trinity aquifers. A simplification is to assume laminar flow everywhere and an effective transmissivity, so that results are consistent with known hydraulic gradients. The only method to mathematically approximate the effect of horst and graben structural control on lateral ground-water movement in a bedded carbonate unit is to vary transmissivity and to vary the direction and

magnitude of anisotropy in a model layer. The range in transmissivity and storage coefficients for the Edwards aquifer used in the model were taken from maps and data published in Maclay and Small (1984); Hovorka and other (1993); and Hovorka and others (1995). In the Hill Country, hydraulic properties for the Trinity aquifer were obtained from well test data and from calibration of a regional one-layer model (Kuniansky and Holligan, 1994). Vertical leakage coefficients between layers were estimated from confining unit thickness (Barker and Ardis, 1996) and rock properties, but were adjusted to be leakier in areas where data indicate cross-formational flow along faults and joints.

A modified version of MODFE (Torak, 1992), a two-dimensional finite-element ground-water flow model was used to simulate ground-water flow in the karstic Edwards aquifer system. This code has not been tested elsewhere, thus, programming errors may exist in the code. Verification of the model code was conducted by comparing the results of an equivalent finite-element mesh (Kuniansky, 1990) using the MODFLOW (McDonald and Harbaugh, 1988) model; both model codes appear to simulate similar ground-water levels and head-dependent flux values. A 20-hour simulation time for 1978-89 using monthly stress periods made parameter estimation and calibration difficult. Thus, it is likely that the model calibration could be improved. Additionally, the lower layer of the model was simulated as a constant head layer using the steady-state simulated initial conditions with both layers actively simulated. This was incorporated to eliminate transient instability in the solution for head in the lower model layer. Transient instability occurred during efforts to simulate the 12 highest monthly recharge events conducted over 144 monthly stress periods within small areas in the lower model layer (relatively low permeability Trinity aquifer beneath outcrop of high permeability Edwards aquifer). The solution for head in the Edwards aquifer did not change as a result of simulating the lower layer as constant head rather than active during the transient simulation.

With all of the limitations described above, simulated heads, spring flows, and base flows reasonably match observed data (Kuniansky and Ardis, [in press]) and transmissivities used for the Edwards aquifer fall within the ranges published by Maclay and Small (1984) and Hovorka and others (1995). Thus, the estimated direction of flow and Darcy flux along selected flow paths is considered to be reasonable. The least conclusive aspect of the analysis is associated with estimates of pore velocity and times of travel due to the poor understanding of effective aquifer thickness or the distribution of effective porosity within the Edwards aquifer.

Table 1. Summary of flow path analysis for average simulated potentiometric surface, 1978-89.

Flowpath Number and description	Thickness <sup>1</sup> (feet) minimum to maximum, average	Porosity <sup>1</sup> (percent) minimum to maximum, average	Distance (miles)	Average Velocity (feet per day) minimum to maximum Average	Time (years) minimum to maximum
1. West Nueces River to Comal Springs	450 to 850, 620	15 to 35, 23	180	0.024 to 50, 6.9	350 to 4,300
2. Nueces River to Comal Springs	450 to 850, 610	15 to 35, 22	149	0.024 to 50, 8.1	210 to 2,600
3. Frio River to Comal Springs	450 to 850, 600	15 to 35, 22	122	0.40 to 50, 9.8	69 to 790
4. Sabinal River to Comal Springs	450 to 850, 580	15 to 35, 23	114	0.017 to 50, 9.8	65 to 780
5. Hondo Creek to Comal Springs	450 to 750, 560	15 to 35, 22	120	0.99 to 60, 12	49 to 600
6. Verde Creek to Comal Springs	450 to 750, 530	15 to 28, 22	111	0.65 to 50, 13	29 to 360
7. Northwest of San Antonio to Comal Springs	450 to 450, 450	15 to 28, 24	46	0.24 to 50, 14	27 to 320
8. Cibolo Creek to Comal Springs	350 to 450, 430	15 to 28, 24	43	0.05 to 50, 15	200 to 2,400
9. Guadalupe River to San Marcos Springs	400 to 500, 460	24 to 28, 26	16	0.14 to 23, 8.6	23 to 270
10. Blanco River to San Marcos Springs	400 to 500, 450	24 to 28, 26	8	0.30 to 7.3, 2.7	14 to 160

<sup>1</sup> From Hovorka and others, 1993

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