Analysis of Groundwater Flow in the Edwards Limestone Aquifer, San Antonio Area, Texas

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science, in Hydrology

by

Donald Alan Mahin

Mines Library
University of Nevada - Reno
Reno, Nevada 89557

July 1978
The thesis of Donald Alan Mahin is approved:

Michael C. Campana
Thesis Advisor

Department Chairman

Dean, Graduate School

University of Nevada
Reno

July 1978
ACKNOWLEDGMENTS

The author gratefully acknowledges the advice and guidance of Dr. Michael E. Campana in all stages of the author's graduate study at the University of Nevada, Reno. Additional guidance was provided by Drs. John W. Bird, Donald K. Fronek, and David L. Koch as members of the author's graduate committee. Special thanks are extended to the author's colleagues, family, and friends for their advice, encouragement, and patience.

Financial support was provided by the Division of Earth Sciences, National Science Foundation (NSF Grant EAR-77-13633), the United States Geological Survey, the Office of Water Research and Technology and the Desert Research Institute, University of Nevada System.
ABSTRACT

The Edwards Limestone aquifer of south-central Texas, a highly fractured and faulted group of limestone formations, is the only supply of water to the San Antonio area. A tritium-calibrated discrete-state compartment model, based upon the conservation of mass within 34 sub-regions of the aquifer, was used to analyze the flow system in the San Antonio area. The aquifer receives recharge from stream losses and direct infiltration of precipitation in the outcrop area of the aquifer in the northern part of the study area. Flow within the aquifer is generally to the east and northeast, along the trend of the Balcones fault zone.
## TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>ACKNOWLEDGMENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>vi</td>
</tr>
<tr>
<td><strong>CHAPTER</strong></td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Groundwater Flow in Fractured and Cavernous Rocks</td>
<td>1</td>
</tr>
<tr>
<td>Discrete-State Compartment Model</td>
<td>3</td>
</tr>
<tr>
<td>2. THE EDWARDS LIMESTONE AQUIFER</td>
<td>9</td>
</tr>
<tr>
<td>Location and Extent</td>
<td>9</td>
</tr>
<tr>
<td>Hydrogeology</td>
<td>11</td>
</tr>
<tr>
<td>3. APPLICATION OF DISCRETE-STATE COMPARTMENT MODEL TO THE EDWARDS LIMESTONE AQUIFER</td>
<td>16</td>
</tr>
<tr>
<td>Calibration and Validation</td>
<td>22</td>
</tr>
<tr>
<td>4. INTERPRETATION OF FLOW SYSTEM AND RECHARGE FROM THE DISCRETE-STATE COMPARTMENT MODEL</td>
<td>36</td>
</tr>
<tr>
<td>5. CONCLUSIONS AND RECOMMENDATIONS</td>
<td>46</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>48</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Fractions of annual recharge</td>
<td>19</td>
</tr>
<tr>
<td>3.2 Cell areas, volumes and effective porosities</td>
<td>33</td>
</tr>
<tr>
<td>3.3 Discharge volumes</td>
<td>34</td>
</tr>
<tr>
<td>4.1 Flow paths</td>
<td>39</td>
</tr>
<tr>
<td>4.2 Average annual recharge 1953-1971</td>
<td>41</td>
</tr>
<tr>
<td>4.3 Estimated annual recharge volume</td>
<td>42</td>
</tr>
<tr>
<td>4.4 Fractions of average annual recharge by source</td>
<td>43</td>
</tr>
</tbody>
</table>
# LIST OF ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Location</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Limits of Edwards Limestone aquifer near San Antonio</td>
<td>13</td>
</tr>
<tr>
<td>3.1</td>
<td>Tritium distribution</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Cell boundaries</td>
<td>21</td>
</tr>
<tr>
<td>3.3</td>
<td>Cell 11 tritium concentrations</td>
<td>23</td>
</tr>
<tr>
<td>3.4</td>
<td>Cell 13 tritium concentrations</td>
<td>24</td>
</tr>
<tr>
<td>3.5</td>
<td>Cell 18 tritium concentrations</td>
<td>25</td>
</tr>
<tr>
<td>3.6</td>
<td>Cell 19 tritium concentrations</td>
<td>26</td>
</tr>
<tr>
<td>3.7</td>
<td>Cell 20 tritium concentrations</td>
<td>27</td>
</tr>
<tr>
<td>3.8</td>
<td>Cell 29 tritium concentrations</td>
<td>28</td>
</tr>
<tr>
<td>3.9</td>
<td>Cell 31 tritium concentrations</td>
<td>29</td>
</tr>
<tr>
<td>4.1</td>
<td>Edwards Limestone aquifer flow system</td>
<td>37</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Groundwater Flow in Fractured and Cavernous Rocks

Groundwater flow through most porous media is laminar flow and may be described by Darcy's Law. In fractured and cavernous rocks, groundwater flow can be some combination of laminar and turbulent flow.

Limestone aquifers, especially those with large solution cavities, have flow systems which may not follow Darcy's Law. The flow of groundwater through these aquifers can be laminar, nonlinear laminar, or turbulent flow. One possible generalization of this flow can be expressed as (after Madhav and Basak, 1977):

\[ \bar{V}_i = \alpha_i K_i S_i + \beta_i C_i S_i^n \]  

(1.1)

where,

- \( \bar{V}_i \) = average velocity in the "i" direction;
- \( \alpha_i \) = weighting factor for laminar flow;
- \( \beta_i \) = weighting factor for nonlinear flow;
- \( K_i \) = hydraulic conductivity in the "i" direction;
- \( C_i \) = parameter of nonlinear flow in the "i" direction;
- \( S_i \) = gradient of hydraulic head in the "i" direction; and
- \( n \) = exponent of gradient for nonlinear flow.

In most studies of fracture or solution channel
groundwater flow, the aquifer parameters are unknown or roughly estimated. The known information is usually limited to head distributions, tracer concentrations, estimated recharge volumes, spring discharges, and pumping data. The uncertainties in the known data are those in the data collection. Determination of the aquifer parameters from the known data is called system identification (Hart and Yao, 1977). Aquifer models based upon equation 1.1 or similar relationships are difficult to use for system identification, since the equation of motion (1.1) will not yield a unique solution for the aquifer parameters. Iterative methods exist which can be used to determine the model parameters in a least squares, weighted least squares, or Bayesian framework (Hart and Yao, 1977). These methods require a detailed knowledge of the physical configuration of the system.

Groundwater flow models of fractured and cavernous aquifers are generally one of the following types:

i) Finite difference or finite element models based upon Darcy's Law, ignoring the possible nonvalidity of Darcy's Law;

ii) Statistical models, which relate input to output without considering the physical processes involved;

iii) Analog models, which require a detailed know-
ledge of the system to be modeled;

iv) Discrete-state compartment models, which are based upon physical laws and are represented by a set of recursive equations.

Of the various models listed, the discrete-state compartment (DSC) model is the only one which combines physical and operational aspects of modeling. The DSC model is designed so that certain physical laws are followed, without the need to know the exact physical system or its parameters. This model is well-suited for complex flow systems like those in rocks which contain jointing, fractures, solution channels, or lava tubes.

**Discrete-State Compartment Model**

For this study, a discrete-state compartment (DSC) model was developed based upon the model by Simpson and Duckstein (1976). Campana (1975) wrote a generalized computer program (DISCOM) and applied the model to groundwater systems.

The DSC model represents the physical system as a set of interconnected cells, in which water and dissolved material are transported in accordance with physical laws. Transport of water and dissolved material is governed by a set of recursive equations which represent the physical system as a series of discrete states. The DSC model uses the law of conservation of mass as a con-
straint in the derivation of the recursive equations.

Each cell in the DSC model represents a region of the physical system. The area represented by each cell is determined from the uniformity of the sub-area of the system and the data availability. Cells may be arranged in any manner in space, so that the DSC model may represent a one-, two-, or three-dimensional system.

Tracers may represent real substances which are dissolved in the water or they may serve as numerical labels to identify water as it passes through the model. The amount of tracer in a cell is called the cell state. In this DSC model, the cell state represents the mass of tracer within a cell. The concentration of tracer is uniform within a single cell. Concentration gradients may exist only between individual cells.

The state of each cell in the DSC model is determined by a discrete form of the continuity equation. The state of any cell can be expressed as (after Simpson and Duckstein, 1976):

\[ S(N+1, J) = S(N, J) + \{BRV(N+1, J) \times BRC(N+1, J)\} - \{BDV(N+1, J) \times BDC(N+1, J)\} + R(N+1, J) \]  

where,

- \( S \) = cell state;
- \( BRV \) = boundary recharge volume;
- \( BRC \) = boundary recharge concentration;
- \( BDV \) = boundary discharge volume;
- \( BDC \) = boundary discharge concentration;
- \( R \) = rate of change of cell state.
BDV = boundary discharge volume;
BDC = boundary discharge concentration;
R = tracer source or sink;
N = iteration number; and
J = cell number.

All volume terms in the DSC model are expressed as a multiple of an arbitrary unit reference volume (URV). The generalized DSC model allows cell volumes to change or remain constant with time. In this study, cell volumes will remain constant with time.

Iterations of the DSC model can represent steps in real time. The length of the real time step is determined by the modeler and is dependent upon the available data. The real time step and the observed (or estimated) recharge rates determine the system recharge boundary volumes (SBRV). With recharge rate as a function of time and space:

\[ SBRV(N, J) = \frac{\bar{Q}(N, J) \cdot \Delta t}{URV} \]  

(1.3)

where,

SBRV = system boundary recharge volume;
\( \bar{Q} \) = average recharge rate;
\( \Delta t \) = real time step;
N = iteration number;
J = cell number; and
URV = unit reference volume.
Radioactive decay of tracers is accounted for by a radioactive decay factor (RD). In equation form, the adjusted cell state is represented as:

$$S'(N+1,J) = S(N+1,J) \times RD$$

where,

- $S =$ cell state;
- $S' =$ cell state adjusted for radioactive decay;
- $RD = e^{-\lambda(\Delta t)}$;
- $\lambda = (\ln 2)/T_{1/2}$;
- $T_{1/2} =$ half-life of tracer; and
- $\Delta t =$ real time step in the same units as $T_{1/2}$.

The DSC model, with constant cell volumes, functions in response to the system boundary recharge volumes and concentrations. Since no cell volume changes are allowed, the discharge volume of any cell equals the recharge volume which was added to the cell.

To solve equation 1.2 it is necessary to know the values of the terms on the right side of the equation. The boundary discharge concentration (BDC) is the only term which is left to be defined. Two alternative definitions for the BDC are included in DISCOM: one based upon a simple mixing cell (SMC), and the other on a modified mixing cell (MMC).

In the simple mixing cell (SMC), perfect mixing is simulated by assuming that the cell walls expand to
accommodate the recharge volume of water. The incoming water and tracer mix completely with the cell contents before the cell is allowed to discharge. The BDC for the SMC is defined as the concentration of tracer in the cell in its expanded condition:

\[ BDC(N+1, J) = \frac{S(N, J) + \{BRC(N+1, J) \times BRV(N+1, J)\}}{VOL(J) + BRV(N+1, J)} \]  

where,

\[ VOL(J) = \text{volume of cell } J. \]

The modified mixing cell (MMC) is a rigid cell with the BDC defined as the concentration of tracer in the cell at the previous iteration:

\[ BDC(N+1, J) = \frac{S(N, J)}{VOL(J)} \]  

The MMC approaches pure piston flow as the BRV approaches the cell volume (VOL), and approaches perfect mixing (SMC) as the BRV approaches zero. This study is limited to a model with all cells following the MMC mixing rule to define boundary discharge concentrations (BDC). This limitation assures constant cell volumes and is more consistent with the mixing in short real time steps.

The DSC model allows the flow paths between the cells and discharges from the system to be specified by the modeler. This requires some knowledge of the flow system to obtain the initial set of specifications of the flow system. These specifications are adjusted by
the modeler in the calibration process to obtain agree-
ment between the model predicted tracer concentrations
and the observed tracer concentrations.

During each iteration, the following operations are
performed upon each cell:

i) Recharge + Discharge;

ii) Mixing of water within the cell; and

iii) Radioactive decay of tracer isotopes.

This DSC model is limited in application to systems
with relatively constant volumes. Effects caused by
changes in hydraulic head gradients are not included in
the DSC model. Thick confined limestone aquifers, such
as the Edwards Limestone aquifer, have relatively con-
stant storage volumes.
CHAPTER 2

THE EDWARDS LIMESTONE AQUIFER

Location and Extent

The Edwards Limestone aquifer of south central Texas extends from Austin southwest through San Antonio and west to Comstock, near the Mexican border (Figure 2.1). The central portion of the aquifer, between the groundwater divides at Brackettville on the west and Kyle on the northeast, is the only water supply for the city of San Antonio, four military bases, numerous farms and ranches, and several other cities. San Antonio is the largest city in the United States which depends entirely upon groundwater (Green, 1965). This study is limited to the central portion of the Edwards Limestone aquifer near San Antonio.

The confined portion of the aquifer is limited by the outcrop of the aquifer to the north and northwest along the base of the Edwards Plateau and to the south and southeast by a zone of low permeability, characterized by water containing more than 1000 parts per million total dissolved solids. This line of demarcation in water quality and permeability is called the "Bad Water Line" and is thought to be the southern limit of secondary permeability development. The area south of the
FIGURE 2.1 LOCATION MAP
"Bad Water Line" may have been an ancient groundwater divide (Abbott, 1975). The aquifer width varies from 4 to 32 kilometers (2.5 to 19.9 miles). The length of the confined aquifer between the groundwater divides at Brackettville and Kyle is about 280 kilometers (174 miles), with an area of about 4460 square kilometers (1722 square miles).

Hydrogeology

The Edwards Limestone aquifer is composed of three separate geologic formations which are part of the Comanche Series of Lower Cretaceous age. From oldest to youngest, the Comanche Peak Limestone, Edwards Limestone, and Georgetown Limestone formations comprise the Edwards Limestone aquifer. The average thickness of the aquifer is about 150 meters (500 feet) with reduced thicknesses in the unconfined portions of the aquifer (George, 1952; Arnow, 1962; DeCook, 1963; Welder and Reeves, 1964; Green, 1965).

The aquifer is a highly fractured, hard, light gray group of limestones which contain numerous caverns and solution channels. These forms of secondary porosity result in the anisotropic hydraulic properties of the aquifer (Sayre and Bennett, 1941). The Balcones fault zone, a series of normal faults, coincides with the Edwards Limestone aquifer in the study area. These faults
have individual displacements of up to 213 meters (700 feet) and a maximum combined displacement of about 457 meters (1500 feet) in Comal County (Green, 1965). The Balcones fault zone is the major structural feature in the San Antonio area. The aquifer dips gently to the southeast.

The faults, fractures, and solution channels act as conduits for groundwater flow within the aquifer. Where confined, the aquifer is overlain by the Grayson Shale, a blue-gray clay and clayey shale, which forms the upper confining layer. The Glen Rose Limestone, a relatively impermeable limestone, shale, and dolomite unit, underlies the aquifer. Vertical groundwater flow through the Grayson Shale is limited to fault traces and fractures.

Recharge to the aquifer is from stream losses and direct precipitation on the Edwards Limestone outcrop area (Figure 2.2). Streams flowing across the recharge zone lose most of their base flow and a large portion of their flood flow to infiltration (Green, 1965). Direct precipitation on the recharge zone contributes significantly to the recharge of the aquifer. Local runoff within the recharge zone is minor, due to the rapid infiltration and flow losses in the ephemeral streams.

Natural discharge from the aquifer is through springs. The major springs are located along the normal
FIGURE 2.2 LIMITS OF EDWARDS LIMESTONE AQUIFER NEAR SAN ANTONIO.
faults of the Balcones fault zone. Two of the springs, Comal and San Marcos, are of first magnitude (Meinzer, 1923) with discharges over 2.8317 cubic meters per second (100 cubic feet per second). Artificial discharge from the aquifer is by means of over 4000 wells. These range in type and discharge from small domestic and stock wells to large municipal wells which produce up to 0.568 cubic meters per second (9000 gallons per minute).

The hydraulic head within the aquifer has declined as a result of the well discharges. The change in hydraulic head has not been steady. There have been many fluctuations in the hydraulic head, with a net decline in hydraulic head. Welder and Reeves (1964) reported a maximum hydraulic head variation of approximately 40 meters (131 feet). Changes in aquifer storage can be related to hydraulic head changes by the following equation:

\[
\Delta S = \frac{\Delta H \times S \times 100}{b \times EP}
\]

(2.1)

where,

\( \Delta S \) = percent change in aquifer storage;
\( \Delta H \) = change in hydraulic head;
\( S \) = storage coefficient for aquifer;
\( EP \) = effective porosity of the aquifer; and
\( b \) = aquifer thickness.

The 40 meter variation in hydraulic head represents less than one percent of the aquifer storage. If an
effective porosity of .03 and a storage coefficient of .001 are assumed as conservative estimates of the aquifer parameters, the change in storage is only 0.889 percent of the total aquifer storage.
APPLICATION OF DISCRETE-STATE COMPARTMENT MODEL TO THE EDWARDS LIMESTONE AQUIFER

Environmental tritium, both from natural sources and atmospheric testing of thermonuclear devices, can be used to calibrate and validate a discrete-state compartment model of the Edwards Limestone aquifer. This model differs from the previous tritium-calibrated DSC model (Campana, 1975) in cell configuration, iteration time step, and recharge data preparation. A nineteen-year period, 1953 through 1971, was modeled in the current study.

The data used in the DSC model consist of recharge estimates (Garza, 1966), tritium concentrations in precipitation (International Atomic Energy Agency, 1969; 1970; 1971; 1973; 1975) groundwater tritium concentrations within the Edwards Limestone aquifer (Pearson et al., 1975), estimates of the discharge from the aquifer, and tritium concentrations in the Nueces River (Pearson et al., 1975). The precipitation tritium data through 1961 were measured at Ottawa, Ontario, Canada and after 1961 at Waco, Texas.

System boundary recharge concentrations of the environmental tritium tracer used in the DSC model were
estimated from the Waco precipitation tritium measurements and estimates. To obtain estimates of the recharge concentrations, it was necessary to assume the tritium concentrations in the Nueces River approximated the tritium concentrations in the recharge which resulted from stream losses. It was further assumed that half of the recharge to the aquifer is from stream losses (Pearson et al., 1975) and that Waco precipitation does not significantly differ from precipitation in the San Antonio area in terms of tritium concentration. A regression analysis of Nueces River tritium concentrations as a function of Waco precipitation tritium concentrations yields:

\[ T(M,R) = 5.2114 \times \{T(M-1,W)\}^{0.56515} \]  

(3.1)

where,

\[ T = \text{tritium concentration in tritium units} \]

\[ (1 \text{ tritium unit} = 1 \text{ tritium atom/}10^{18} \text{ hydrogen atoms}); \]

\[ M = \text{month number}; \]

\[ R = \text{Nueces River}; \]

\[ W = \text{Waco precipitation}. \]

The correlation coefficient of equation 3.1 is 0.8435. A sample length of 27 months was used.

The recharge concentration is defined by:

\[ SBRC(M) = 0.5 \times \{T(M,W)+T(M,R)\} \]  

(3.2)

where,
SBRC = system boundary recharge concentration.
The recharge concentration used as input to the model is the arithmetic average of the values given by equation 3.2 for the three-month period of real time represented by each iteration.

For the period of time from 1953 to 1961, Waco precipitation tritium concentrations were estimated by:

\[ T(M,W) = 0.85912 \times [T(M,O)]^{0.84176} \] (3.3)

where,

- \( T \) = tritium concentration in tritium units;
- \( M \) = month number;
- \( W \) = Waco precipitation; and
- \( O \) = Ottawa precipitation.

The correlation coefficient of equation 3.3 is 0.8539. A sample length of 91 months was used.

Recharge volume estimates for eight basins which supply recharge to the Edwards Limestone aquifer are tabulated in Garner and Shih (1973). These estimates are based upon measured and estimated stream losses in the recharge zone and from estimates of direct recharge from precipitation on the recharge zone (Garza, 1966).

To obtain recharge volume estimates for each of the three month time periods, it was necessary to assign a constant fraction of the annual recharge to each calendar quarter. Recharge was assumed to have the same
distribution in time as precipitation at San Antonio.
Average precipitation data from the San Antonio airport (Arnow, 1963) was used to obtain the fractions of annual recharge (Table 3.1) for each calendar quarter.

For this study, a unit reference volume (URV) of one cubic kilometer ($10^9 m^3$) was used. All volumes used in the DSC model are expressed as multiples of the URV.

Table 3.1. Fractions of Annual Recharge.

<table>
<thead>
<tr>
<th>QUARTER</th>
<th>MONTHS</th>
<th>PERCENT RECHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>January</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>February</td>
<td></td>
</tr>
<tr>
<td></td>
<td>March</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>April</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td></td>
</tr>
<tr>
<td></td>
<td>June</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>July</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td></td>
</tr>
<tr>
<td></td>
<td>September</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>October</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>November</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December</td>
<td></td>
</tr>
</tbody>
</table>

Cell boundaries were determined by examining the tritium distribution (Figure 3.1) within the aquifer, giving consideration to the uniformity of each area and the amount of available data. The resulting cell boundaries are shown in Figure 3.2. Initial cell volumes were estimated using an effective porosity of 0.03 and a thickness of 150 meters.

Initial tritium concentrations were estimated for
FIGURE 3.1 Tritium Distribution

EXPLANATION

- Lines of Equal Tritium Content Values in Tritium Units

(After Pearson, et al., 1975)
FIGURE 3.2 Cell Boundaries.
each cell, using the observed tritium distribution as a guide.

**Calibration and Validation**

The observed aquifer tritium concentration data were separated into two groups. The first group contained twelve observations from throughout the confined portion of the aquifer and was reserved for model validation. The second group contained sixty-three observations from the entire aquifer and was used for model calibration.

A trial and error procedure was used to calibrate the DSC model. The computer program (DISCOM) was run with the initial estimates of the various model parameters, which were then adjusted to obtain a satisfactory agreement between the calibration data and the DSC model predicted tritium concentrations. In this process the cell volumes, flow paths, and recharge volumes were adjusted with consideration given to the physical limitations of the aquifer. Calibration decisions were evaluated on the basis of minimizing the error for each of the cells which possessed calibration data.

The observed tritium concentrations and the DSC model predicted tritium concentrations for some of the cells are shown in Figures 3.3 to 3.9. The observed tritium concentrations are bounded by a one standard deviation confidence band which represents a 68 percent confidence
FIGURE 3.4

CELL 13 TRITIUM CONCENTRATIONS

T.U.

10

5

1955 1960 1965 1970

YEAR
FIGURE 3.5   CELL 18  TRITIUM CONCENTRATIONS
FIGURE 3.6  CELL 19  TRITIUM CONCENTRATIONS
FIGURE 3.8  CELL 29  TRITIUM CONCENTRATIONS
In each DSC model cell, the observed data were assumed to be representative of the entire cell. This assumption is necessary to calibrate the model using environmental tritium as a tracer.

Figures 3.3, 3.4, and 3.5, representing cells 13, 19, and 20, respectively, show the response of the model in areas near the northern edge of the confining aquifer. The DSC model and the aquifer respond similarly in these areas with no significant time lags or attenuation of peaks in the model. The initial estimate of tritium concentration may have been somewhat excessive in cells 13 and 19.

Cells 18 and 20, represented by Figures 3.6 and 3.7, are examples of cells with low tritium concentrations. These cells may have received limited quantities of bomb tritium as evidenced by the observed data. The model simulated tritium concentrations shown in Figure 3.9 cell 31 tritium concentrations show an increase in tritium concentration in 1971 which may represent the bomb tritium. Cells 17 and 23 are similar to cells 18 and 20 in model response and observed tritium concentrations.

**FIGURE 3.9  CELL 31 TRITIUM CONCENTRATIONS**
interval. Cells which were not graphed had little or no observed data.

In each of the DSC model cells with observed data it was assumed that the well with observed data was representative of the entire cell. This assumption is necessary to permit model calibration using environmental tritium as a tracer.

Figures 3.3, 3.4, and 3.6, representing cells 11, 13, and 19 respectively, show the response of the DSC model in areas near the northern edge of the confined aquifer. The DSC model and the aquifer respond similarly in these areas with no significant time lags or attenuation of peaks in the model. The initial estimates of tritium concentration may have been somewhat excessive in cells 13 and 19.

Cells 18 and 20, represented by figures 3.5 and 3.7, are examples of cells with low tritium concentrations. These cells may have received limited quantities of bomb tritium as evidenced by the observed data. The DSC model simulated tritium concentrations show an increase in tritium concentration in 1971 which may represent the bomb tritium. Cells 17 and 23 are similar to cells 18 and 20 in model response and observed tritium concentrations.

Comal and San Marcos Springs (Figures 3.8 and 3.9)
are located low in the aquifer flow system. The model simulated tritium concentrations for these springs do not closely correspond to the observed tritium concentrations. The DSC model lags behind the observed data at San Marcos Springs (cell 31). At Comal Springs, the DSC model is somewhat responsive to the bomb tritium as seen in Figure 3.8. Errors in the DSC model simulated tritium concentrations for Comal and San Marcos Springs are the result of attenuation and errors in the entire model up gradient from the springs.

The tritium concentrations predicted by the DSC model do not respond as rapidly to changes in recharge concentrations as the observed tritium concentrations. This is, in part, the result of the data preparation and the nature of the model. Extreme events were eliminated by averaging the recharge tritium concentrations over the three-month real time steps in the DSC model. Within the model impulses of tritium are further attenuated by the requirement for uniform concentrations within each cell.

In the real aquifer, impulses may be transmitted by fractures and solution channels without reaching equilibrium with the water in the primary pore spaces. The DSC model considers each cell to be uniform in all respects, which may not be true in the aquifer.
The land area and calibrated volume of each cell, along with the effective porosities of the cells in the confined aquifer are listed in Table 3.2. The aquifer thickness is not certain in the unconfined portion; therefore effective porosities have not been calculated for cells 1 through 8.

Tritium concentrations and discharge volumes were used to validate the DSC model. A correlation coefficient of 0.9275 was calculated for the validation data set and the corresponding DSC model predicted tritium concentrations. The calibration data, from the cells with validation data, were also used to calculate a correlation coefficient of 0.9450. These correlation coefficients show that there is significant correlation (at a 95 percent confidence level) between the modeled and observed tritium concentrations in both calibration and validation data sets.

The observed discharge volumes and the DSC model predicted discharge volumes were compared and found to be similar (Table 3.3). The observed discharge volumes contained well discharges which are a function of demand. The DSC model calculates discharges as a function of recharge, so some differences are expected.

The high correlation of the tritium concentrations and the similarity in the discharge volumes show that the DSC model has the ability to simulate the tritium
Table 3.2

CELL AREAS, VOLUMES, AND EFFECTIVE POROSITIES

<table>
<thead>
<tr>
<th>Cell</th>
<th>Land Area (km²)</th>
<th>Volume (km³)</th>
<th>Effective Porosity (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>798</td>
<td>2.6600</td>
<td>N.C.</td>
</tr>
<tr>
<td>2</td>
<td>490</td>
<td>2.2655</td>
<td>N.C.</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>1.7500</td>
<td>N.C.</td>
</tr>
<tr>
<td>4</td>
<td>306</td>
<td>2.0180</td>
<td>N.C.</td>
</tr>
<tr>
<td>5</td>
<td>182</td>
<td>0.5055</td>
<td>N.C.</td>
</tr>
<tr>
<td>6</td>
<td>310</td>
<td>0.6100</td>
<td>N.C.</td>
</tr>
<tr>
<td>7</td>
<td>360</td>
<td>2.3000</td>
<td>N.C.</td>
</tr>
<tr>
<td>8</td>
<td>200</td>
<td>1.1000</td>
<td>N.C.</td>
</tr>
<tr>
<td>9</td>
<td>270</td>
<td>3.2000</td>
<td>7.90</td>
</tr>
<tr>
<td>10</td>
<td>130</td>
<td>0.9500</td>
<td>4.87</td>
</tr>
<tr>
<td>11</td>
<td>145</td>
<td>0.6880</td>
<td>3.16</td>
</tr>
<tr>
<td>12</td>
<td>173</td>
<td>1.5500</td>
<td>5.97</td>
</tr>
<tr>
<td>13</td>
<td>373</td>
<td>2.8900</td>
<td>5.17</td>
</tr>
<tr>
<td>14</td>
<td>240</td>
<td>1.9500</td>
<td>5.42</td>
</tr>
<tr>
<td>15</td>
<td>207</td>
<td>1.5500</td>
<td>4.99</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
<td>1.0000</td>
<td>6.67</td>
</tr>
<tr>
<td>17</td>
<td>380</td>
<td>4.5500</td>
<td>7.98</td>
</tr>
<tr>
<td>18</td>
<td>473</td>
<td>2.1000</td>
<td>2.97</td>
</tr>
<tr>
<td>19</td>
<td>380</td>
<td>2.0000</td>
<td>3.51</td>
</tr>
<tr>
<td>20</td>
<td>330</td>
<td>1.7400</td>
<td>3.52</td>
</tr>
<tr>
<td>21</td>
<td>330</td>
<td>0.5120</td>
<td>4.02</td>
</tr>
<tr>
<td>22</td>
<td>148</td>
<td>0.9410</td>
<td>4.24</td>
</tr>
<tr>
<td>23</td>
<td>447</td>
<td>1.4500</td>
<td>2.16</td>
</tr>
<tr>
<td>24</td>
<td>81</td>
<td>0.4850</td>
<td>3.99</td>
</tr>
<tr>
<td>25</td>
<td>125</td>
<td>0.7700</td>
<td>4.11</td>
</tr>
<tr>
<td>26</td>
<td>58</td>
<td>0.2660</td>
<td>3.06</td>
</tr>
<tr>
<td>27</td>
<td>53</td>
<td>0.6000</td>
<td>7.62</td>
</tr>
<tr>
<td>28</td>
<td>50</td>
<td>0.1445</td>
<td>1.93</td>
</tr>
<tr>
<td>29</td>
<td>46</td>
<td>0.3106</td>
<td>4.50</td>
</tr>
<tr>
<td>30</td>
<td>37</td>
<td>0.2965</td>
<td>5.28</td>
</tr>
<tr>
<td>31</td>
<td>32</td>
<td>0.1936</td>
<td>4.09</td>
</tr>
<tr>
<td>32</td>
<td>17</td>
<td>0.2000</td>
<td>7.62</td>
</tr>
<tr>
<td>33</td>
<td>35</td>
<td>0.2740</td>
<td>5.28</td>
</tr>
<tr>
<td>34</td>
<td>46</td>
<td>0.2850</td>
<td>4.09</td>
</tr>
</tbody>
</table>

Totals 7181 44.1051

NOTE: N.C. = not calculated, formation thickness uncertain.
<table>
<thead>
<tr>
<th>COUNTIES AND DISCHARGING CELLS</th>
<th>YEAR</th>
<th>DSC MODEL</th>
<th>OBSERVED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uvalde</td>
<td>1964</td>
<td>0.0569</td>
<td>0.0606</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>0.0515</td>
<td>0.0575</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>0.0874</td>
<td>0.0596</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>0.0559</td>
<td>0.0998</td>
</tr>
<tr>
<td></td>
<td>1968</td>
<td>0.0810</td>
<td>0.0714</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>0.0654</td>
<td>0.1089</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>0.0680</td>
<td>0.1242</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>0.1369</td>
<td>0.1441</td>
</tr>
<tr>
<td>Medina</td>
<td>1964</td>
<td>0.0131</td>
<td>0.0107</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>0.0138</td>
<td>0.0123</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>0.0224</td>
<td>0.0128</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>0.0165</td>
<td>0.0187</td>
</tr>
<tr>
<td></td>
<td>1968</td>
<td>0.0243</td>
<td>0.0122</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>0.0175</td>
<td>0.0168</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>0.0191</td>
<td>0.0203</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>0.0343</td>
<td>0.0399</td>
</tr>
<tr>
<td>Bexar</td>
<td>1964</td>
<td>0.1399</td>
<td>0.2487</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>0.1784</td>
<td>0.2481</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>0.2235</td>
<td>0.2445</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>0.1714</td>
<td>0.2957</td>
</tr>
<tr>
<td></td>
<td>1968</td>
<td>0.2966</td>
<td>0.2554</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>0.1889</td>
<td>0.2668</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>0.2147</td>
<td>0.2841</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>0.2854</td>
<td>0.3242</td>
</tr>
<tr>
<td>Comal</td>
<td>1964</td>
<td>0.1143</td>
<td>0.1758</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>0.1546</td>
<td>0.2402</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>0.1706</td>
<td>0.2451</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>0.1331</td>
<td>0.1716</td>
</tr>
<tr>
<td></td>
<td>1968</td>
<td>0.2458</td>
<td>0.2937</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>0.1524</td>
<td>0.2691</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>0.1751</td>
<td>0.2826</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>0.2689</td>
<td>0.2075</td>
</tr>
<tr>
<td>Hays</td>
<td>1964</td>
<td>0.1143</td>
<td>0.0904</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>0.2449</td>
<td>0.1558</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>0.1378</td>
<td>0.1423</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>0.1176</td>
<td>0.1015</td>
</tr>
<tr>
<td></td>
<td>1968</td>
<td>0.2591</td>
<td>0.1811</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>0.1859</td>
<td>0.1506</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>0.2158</td>
<td>0.1848</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>0.1985</td>
<td>0.1222</td>
</tr>
</tbody>
</table>
distribution within the aquifer and the discharges from the aquifer. The flow within the aquifer system is probably similar to the flow system described by the DSC model. Flow systems defined by the use of DSC models are not necessarily unique solutions. Minor variations in DSC model flow system will yield insignificant changes in the tritium concentrations and discharge volumes predicted by the DSC model.

The aquifer storage volume can be estimated from the cell volumes in the DSC model. The sum of the cell volumes in the confined portion of the aquifer yields a storage volume of 50.3 cubic kilometers (11,990,000 acre-feet). This storage volume represents an average effective porosity of 4.47 percent in the confined aquifer.

The groundwater flow system is shown in Figure 3.1. Most of the flow in the confined aquifer is to the east and northeast, paralleling the Salton Sea fault zone. The groundwater divides out at point intersections. Groundwater flows away from the groundwater divide which results in flow to the southeast in the area map the Kyle groundwater divide.

The flow paths in the DSC model represent the areal
CHAPTER 4

INTERPRETATION OF FLOW SYSTEM AND RECHARGE FROM THE DISCRETE-STATE COMPARTMENT MODEL

The discrete-state compartment model of the Edwards Limestone aquifer contains a set of specifications for the aquifer storage, flow system, and recharge. These specifications are the result of model calibration using historical data. With proper model calibration, the properties of the DSC model should be good estimates of the aquifer properties.

The aquifer storage volume can be estimated from the cell volumes in the DSC model. The sum of the cell volumes in the confined portion of the aquifer gives a storage volume of 30.9 cubic kilometers (25,000,000 acre-feet). This storage volume represents an average effective porosity of 4.62 percent in the confined aquifer.

The groundwater flow system is shown in Figure 4.1. Most of the flow in the confined aquifer is to the east and northeast, paralleling the Balcones fault zone. The groundwater divides act as no-flow boundaries. Groundwater flows away from the groundwater divides which results in flow to the southwest in the area near the Kyle groundwater divide.

The flow paths in the DSC model represent the aver-
EDWARDS LIMESTONE AQUIFER FLOW SYSTEM

→ FLOW PATH

→ SYSTEM DISCHARGE FLOW PATH

FIGURE 4.1
age flow paths for the simulation period. The actual flow paths in the aquifer vary as a function of the unsteady hydraulic head distribution and system discharge flow paths vary as a function of hydraulic head and the demand for well water. Table 4.1 is a list of the flow paths in the DSC model of the Edwards Limestone aquifer.

Recharge volumes were adjusted in the DSC model calibration procedure. The adjusted recharge volumes were defined by:

$$SBRV'(N,J) = RF(J) \times SBRV(N,J) \quad (4.1)$$

where,

- $SBRV$ = system boundary recharge volume;
- $SBRV'$ = adjusted system boundary recharge volume;
- $RF$ = recharge adjustment factor;
- $N$ = iteration number; and
- $J$ = cell number

The recharge adjustment factors and the adjusted average annual recharge volumes for the simulation period for each of the 8 recharge cells are listed in Table 4.2. Adjusted annual recharge volumes for each of the eight recharge zone cells are listed in Table 4.3. The average annual recharge for the simulation period is 0.614 cubic kilometers (498,000 acre-feet).
Table 4.1. Flow paths.

<table>
<thead>
<tr>
<th>Output cell</th>
<th>Input cell or system discharge</th>
<th>Fraction of cell discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>0.48</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>0.22</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>0.33</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>0.22</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>0.50</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.50</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>0.70</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>0.60</td>
</tr>
<tr>
<td>4</td>
<td>21</td>
<td>0.40</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>0.40</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>33</td>
<td>0.50</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>12</td>
<td>1.00</td>
</tr>
<tr>
<td>12</td>
<td>14</td>
<td>0.12</td>
</tr>
<tr>
<td>12</td>
<td>13</td>
<td>0.58</td>
</tr>
<tr>
<td>13</td>
<td>15</td>
<td>0.30</td>
</tr>
<tr>
<td>13</td>
<td>16</td>
<td>0.15</td>
</tr>
<tr>
<td>13</td>
<td>17</td>
<td>0.55</td>
</tr>
<tr>
<td>14</td>
<td>17</td>
<td>1.00</td>
</tr>
<tr>
<td>12</td>
<td>D</td>
<td>0.30</td>
</tr>
<tr>
<td>15</td>
<td>16</td>
<td>0.05</td>
</tr>
<tr>
<td>17</td>
<td>18</td>
<td>1.00</td>
</tr>
<tr>
<td>16</td>
<td>18</td>
<td>1.00</td>
</tr>
<tr>
<td>15</td>
<td>19</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>18</td>
<td>0.93</td>
</tr>
<tr>
<td>19</td>
<td>19</td>
<td>0.02</td>
</tr>
<tr>
<td>19</td>
<td>20</td>
<td>0.90</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>0.03</td>
</tr>
<tr>
<td>18</td>
<td>D</td>
<td>0.10</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>0.44</td>
</tr>
<tr>
<td>19</td>
<td>22</td>
<td>0.51</td>
</tr>
<tr>
<td>21</td>
<td>22</td>
<td>0.20</td>
</tr>
<tr>
<td>20</td>
<td>22</td>
<td>0.01</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>0.15</td>
</tr>
<tr>
<td>20</td>
<td>23</td>
<td>0.99</td>
</tr>
<tr>
<td>21</td>
<td>24</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Table 4.1.—Continued

<table>
<thead>
<tr>
<th>Output cell</th>
<th>Input cell or system discharge&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Fraction of cell discharge&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>D</td>
<td>0.10</td>
</tr>
<tr>
<td>22</td>
<td>25</td>
<td>0.70</td>
</tr>
<tr>
<td>22</td>
<td>D</td>
<td>0.15</td>
</tr>
<tr>
<td>24</td>
<td>25</td>
<td>0.25</td>
</tr>
<tr>
<td>24</td>
<td>26</td>
<td>0.01</td>
</tr>
<tr>
<td>25</td>
<td>23</td>
<td>0.20</td>
</tr>
<tr>
<td>24</td>
<td>26</td>
<td>0.60</td>
</tr>
<tr>
<td>24</td>
<td>D</td>
<td>0.15</td>
</tr>
<tr>
<td>25</td>
<td>27</td>
<td>0.64</td>
</tr>
<tr>
<td>25</td>
<td>D</td>
<td>0.15</td>
</tr>
<tr>
<td>23</td>
<td>27</td>
<td>0.35</td>
</tr>
<tr>
<td>23</td>
<td>D</td>
<td>0.65</td>
</tr>
<tr>
<td>26</td>
<td>27</td>
<td>0.02</td>
</tr>
<tr>
<td>26</td>
<td>28</td>
<td>0.97</td>
</tr>
<tr>
<td>26</td>
<td>32</td>
<td>0.01</td>
</tr>
<tr>
<td>27</td>
<td>32</td>
<td>1.00</td>
</tr>
<tr>
<td>32</td>
<td>29</td>
<td>1.00</td>
</tr>
<tr>
<td>28</td>
<td>29</td>
<td>0.07</td>
</tr>
<tr>
<td>33</td>
<td>30</td>
<td>0.18</td>
</tr>
<tr>
<td>33</td>
<td>34</td>
<td>0.82</td>
</tr>
<tr>
<td>28</td>
<td>30</td>
<td>0.93</td>
</tr>
<tr>
<td>34</td>
<td>31</td>
<td>1.00</td>
</tr>
<tr>
<td>29</td>
<td>31</td>
<td>0.01</td>
</tr>
<tr>
<td>29</td>
<td>D</td>
<td>0.99</td>
</tr>
<tr>
<td>30</td>
<td>31</td>
<td>1.00</td>
</tr>
<tr>
<td>31</td>
<td>D</td>
<td>1.00</td>
</tr>
</tbody>
</table>

<sup>a</sup>The letter D in this column indicates a system discharge flow path.

<sup>b</sup>The sum of all fractions from a given output cell equals unity. For example, in the case of cell 29, 0.01 + 0.99 = 1.00.
Table 4.2. Average Annual Recharge, 1953-1971.

<table>
<thead>
<tr>
<th>CELL NUMBER</th>
<th>AVERAGE ANNUAL RECHARGE (km$^3$)</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.13465</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>0.12244</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>0.02965</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>0.06925</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>0.08766</td>
<td>0.74</td>
</tr>
<tr>
<td>6</td>
<td>0.03716</td>
<td>0.85</td>
</tr>
<tr>
<td>7</td>
<td>0.08189</td>
<td>0.77</td>
</tr>
<tr>
<td>8</td>
<td>0.05159</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Tritium concentrations measured in the aquifer and simulated by the DSC model decrease as the distance from the source of recharge increases. This decrease in tritium concentration is the result of the time lag of flow through the aquifer, mixing with water of low tritium concentrations, and the decay of tritium with time.

The average composition of the water in each cell, in terms of recharge sources, was determined using the DSC model (Table 4.4). Constant recharge volumes, based upon the average quarterly recharge, were used in a steady-flow version of the Edwards Limestone aquifer DSC model. This steady-flow model was subjected to a series of simulations.

For each simulation, the water entering the recharge cell under study was labeled with a numerical tracer of 1.00. The model was iterated until the resulting cell states converged to a constant value at three significant figures. The resulting cell states, in terms of concen-
<table>
<thead>
<tr>
<th>Year</th>
<th>Nueces and West Nueces River basins</th>
<th>Frio and Dry Frio River basin</th>
<th>Sabinal and Medina River basins</th>
<th>Cibolo and Dry Comal Creek basins</th>
<th>Blanco River basin and adjacent areas</th>
<th>Area between Sabinal and Medina River basins</th>
<th>Area between Cibolo Creek and Medina River basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>1953</td>
<td>0.0264</td>
<td>0.0169</td>
<td>0.0023</td>
<td>0.0447</td>
<td>0.0386</td>
<td>0.0261</td>
<td>0.0042</td>
</tr>
<tr>
<td>1954</td>
<td>0.0756</td>
<td>0.0355</td>
<td>0.0051</td>
<td>0.0312</td>
<td>0.0080</td>
<td>0.0112</td>
<td>0.0113</td>
</tr>
<tr>
<td>1955</td>
<td>0.1579</td>
<td>0.0248</td>
<td>0.0004</td>
<td>0.0204</td>
<td>0.0030</td>
<td>0.0100</td>
<td>0.0073</td>
</tr>
<tr>
<td>1956</td>
<td>0.0192</td>
<td>0.0047</td>
<td>0.0011</td>
<td>0.0078</td>
<td>0.0020</td>
<td>0.0086</td>
<td>0.0034</td>
</tr>
<tr>
<td>1957</td>
<td>0.1340</td>
<td>0.1500</td>
<td>0.0468</td>
<td>0.0686</td>
<td>0.3632</td>
<td>0.0801</td>
<td>0.1230</td>
</tr>
<tr>
<td>1958</td>
<td>0.3290</td>
<td>0.3367</td>
<td>0.1601</td>
<td>0.1178</td>
<td>0.2453</td>
<td>0.0741</td>
<td>0.2801</td>
</tr>
<tr>
<td>1959</td>
<td>0.1352</td>
<td>0.1784</td>
<td>0.0441</td>
<td>0.1168</td>
<td>0.0711</td>
<td>0.0352</td>
<td>0.0918</td>
</tr>
<tr>
<td>1960</td>
<td>0.1094</td>
<td>0.1438</td>
<td>0.0464</td>
<td>0.1283</td>
<td>0.1460</td>
<td>0.0654</td>
<td>0.1206</td>
</tr>
<tr>
<td>1961</td>
<td>0.1051</td>
<td>0.1698</td>
<td>0.0411</td>
<td>0.1089</td>
<td>0.1011</td>
<td>0.0518</td>
<td>0.1001</td>
</tr>
<tr>
<td>1962</td>
<td>0.0585</td>
<td>0.0523</td>
<td>0.0031</td>
<td>0.0707</td>
<td>0.0225</td>
<td>0.0303</td>
<td>0.0223</td>
</tr>
<tr>
<td>1963</td>
<td>0.0490</td>
<td>0.0303</td>
<td>0.0036</td>
<td>0.0517</td>
<td>0.0194</td>
<td>0.0170</td>
<td>0.0098</td>
</tr>
<tr>
<td>1964</td>
<td>0.1555</td>
<td>0.0618</td>
<td>0.0117</td>
<td>0.0534</td>
<td>0.0466</td>
<td>0.0233</td>
<td>0.0582</td>
</tr>
<tr>
<td>1965</td>
<td>0.1208</td>
<td>0.0932</td>
<td>0.0166</td>
<td>0.0673</td>
<td>0.1052</td>
<td>0.0699</td>
<td>0.0988</td>
</tr>
<tr>
<td>1966</td>
<td>0.2087</td>
<td>0.1504</td>
<td>0.0270</td>
<td>0.0623</td>
<td>0.0607</td>
<td>0.0179</td>
<td>0.0743</td>
</tr>
<tr>
<td>1967</td>
<td>0.1014</td>
<td>0.1548</td>
<td>0.0217</td>
<td>0.0551</td>
<td>0.0523</td>
<td>0.0199</td>
<td>0.0617</td>
</tr>
<tr>
<td>1968</td>
<td>0.1613</td>
<td>0.1976</td>
<td>0.0475</td>
<td>0.0739</td>
<td>0.1100</td>
<td>0.0517</td>
<td>0.1887</td>
</tr>
<tr>
<td>1969</td>
<td>0.1476</td>
<td>0.1277</td>
<td>0.0220</td>
<td>0.0683</td>
<td>0.0912</td>
<td>0.0489</td>
<td>0.0800</td>
</tr>
<tr>
<td>1970</td>
<td>0.1389</td>
<td>0.1593</td>
<td>0.0253</td>
<td>0.0839</td>
<td>0.1039</td>
<td>0.0414</td>
<td>0.0775</td>
</tr>
<tr>
<td>1971</td>
<td>0.3249</td>
<td>0.2384</td>
<td>0.0280</td>
<td>0.0847</td>
<td>0.0752</td>
<td>0.0233</td>
<td>0.1428</td>
</tr>
</tbody>
</table>

**TABLE 4.3**
Estimated Annual Recharge Volumes (km$^3$)
1953-1971
<table>
<thead>
<tr>
<th>Cell</th>
<th>Cell 1</th>
<th>Cell 2</th>
<th>Cell 3</th>
<th>Cell 4</th>
<th>Cell 5</th>
<th>Cell 6</th>
<th>Cell 7</th>
<th>Cell 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.769</td>
<td>0.230</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>0.667</td>
<td>0.333</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>0.418</td>
<td>0.503</td>
<td>0.079</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>14</td>
<td>0.666</td>
<td>0.333</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>0.183</td>
<td>0.220</td>
<td>0.150</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>16</td>
<td>0.374</td>
<td>0.450</td>
<td>0.092</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>17</td>
<td>0.460</td>
<td>0.464</td>
<td>0.064</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>18</td>
<td>0.429</td>
<td>0.454</td>
<td>0.072</td>
<td>0.005</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>19</td>
<td>0.117</td>
<td>0.142</td>
<td>0.097</td>
<td>0.224</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>20</td>
<td>0.418</td>
<td>0.443</td>
<td>0.073</td>
<td>0.013</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>21</td>
<td>0.088</td>
<td>0.106</td>
<td>0.072</td>
<td>0.420</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>22</td>
<td>0.116</td>
<td>0.139</td>
<td>0.092</td>
<td>0.257</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>23</td>
<td>0.353</td>
<td>0.377</td>
<td>0.075</td>
<td>0.63</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>24</td>
<td>0.052</td>
<td>0.063</td>
<td>0.043</td>
<td>0.251</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>25</td>
<td>0.098</td>
<td>0.118</td>
<td>0.078</td>
<td>0.256</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>26</td>
<td>0.025</td>
<td>0.030</td>
<td>0.021</td>
<td>0.118</td>
<td>0.529</td>
<td>0.000</td>
<td>0.226</td>
<td>0.067</td>
</tr>
<tr>
<td>27</td>
<td>0.216</td>
<td>0.238</td>
<td>0.075</td>
<td>0.162</td>
<td>0.012</td>
<td>0.000</td>
<td>0.085</td>
<td>0.172</td>
</tr>
<tr>
<td>28</td>
<td>0.023</td>
<td>0.028</td>
<td>0.019</td>
<td>0.108</td>
<td>0.484</td>
<td>0.085</td>
<td>0.082</td>
<td>0.172</td>
</tr>
<tr>
<td>29</td>
<td>0.199</td>
<td>0.220</td>
<td>0.070</td>
<td>0.157</td>
<td>0.054</td>
<td>0.007</td>
<td>0.213</td>
<td>0.077</td>
</tr>
<tr>
<td>30</td>
<td>0.022</td>
<td>0.026</td>
<td>0.017</td>
<td>0.104</td>
<td>0.464</td>
<td>0.123</td>
<td>0.078</td>
<td>0.165</td>
</tr>
<tr>
<td>31</td>
<td>0.022</td>
<td>0.026</td>
<td>0.017</td>
<td>0.096</td>
<td>0.423</td>
<td>0.193</td>
<td>0.073</td>
<td>0.151</td>
</tr>
<tr>
<td>32</td>
<td>0.214</td>
<td>0.236</td>
<td>0.075</td>
<td>0.161</td>
<td>0.018</td>
<td>0.000</td>
<td>0.224</td>
<td>0.069</td>
</tr>
<tr>
<td>33</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>34</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

TABLE 4.4
Fractions of Average Annual Recharge by Source
tration represent the fraction of water in each cell which entered the recharge boundary cell under study in the simulation. This process was repeated for each of the eight recharge boundary cells.

George (1952) concluded that Hueco and Comal Springs, located in cells 28 and 29 respectively, appear to have separate sources of recharge. The discharge from Hueco Springs has a variable temperature and is often turbid in contrast with the discharge from Comal Springs which has a constant temperature \(23.3^\circ C; 74^\circ F\) and is non-turbid.

The DSC model confirms the different sources of recharge to Hueco and Comal Springs. From Table 4.4 it was determined that about 43 percent of the recharge to Hueco Springs is from the west of Comal County. Comal Springs receives about 94 percent of its recharge from the west of Comal County and 49 percent of the recharge is from Kinney and Uvalde Counties, at the western end of the aquifer.

Similar comparisons may be made for other areas of the aquifer, using Table 4.4 and Figure 4.1. It should be remembered that these recharge fractions are based upon a steady-flow version of the Edwards Limestone aquifer DSC model using the average recharge for the period 1953 to 1971. Future recharge rates may differ from those used in this study; therefore these results
are only relative estimates of the future groundwater flow.
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The discrete-state compartment model of the Edwards Limestone aquifer has been shown to be capable of modeling the transport of tritium within the aquifer. This was done without a knowledge of the intricate interconnections of the solution channels, fractures, and faults. The ability of the DSC model to delineate the transport of tracers and the flow of groundwater without a knowledge of the physical system justifies its use in complex flow systems.

Groundwater flow within the Edwards Limestone aquifer parallels the trend of the Balcones fault zone with restricted flow perpendicular to the fault zone. Some of the faults act as discontinuities in the aquifer, while others act as conduits for groundwater flow. This combination of discontinuity and conduit formation along the faults results in the anisotropic flow system of the Edwards Limestone aquifer.

Future research on the Edwards Limestone aquifer flow system should include a discrete-state compartment model with a shorter time step and additional cells. The present three-month time step attenuates the input pulses of tritium and the recharge events. Monthly time steps
may eliminate this problem. The recharge estimates would then need to be revised using monthly streamflow and precipitation records as a guide. The observed aquifer tritium concentration data may limit the changes in the number of cells.

The DSC model may need to include some 'dead' cells (Simpson and Duckstein, 1976) to represent the primary porosity of the aquifer. These dead cells may allow the model to become more responsive through the reduction of some of the cell volumes.

Discrete-state compartment models, like any other model, are not suited for application to systems which have no observed or estimated data. Hydraulic head is not considered by the DSC model, so the model should not be used to evaluate changes in hydraulic head. With these limitations and the assumption of constant storage volume the DSC model gives relative estimates of the flow system during the simulation period.
REFERENCES CITED


