Online Report 96-3

(CRWR Technical Report 269)

A Parsimonious Model for Simulation of Flow and Transport in a Karst Aquifer

by

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November 1996

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ACKNOWLEDGMENTS

The authors would also like to thank Dr. David Maidment, Dr. Daene McKinney, Dr. Kamy Sepehrnoori, and Dr. Jack Sharp for their suggestions and comments during the course of this study.

Numerous graduate students helped collect and analyze the data used to develop the model. Aaron Kam created the GIS well and water quality database and made the estimates of nitrogen load in septic system effluent. John Meadows helped develop the recharge functions for the creeks that supply water to the aquifer. James Kearley identified the locations and volumes of water wells pumping from the aquifer. Many of the graphics were produced by Ty Lehman, a member of the CRWR staff.

DISCLAIMER

This research project was supported the City of Austin; however, the opinions, findings, conclusions, and recommendations expressed herein are those of the authors and do not necessarily reflect the views of the City of Austin or The University of Texas at Austin.

ABSTRACT

A new type of lumped parameter model was developed to predict the impacts of urban development on water quality and quantity in the Barton Springs portion of the Edwards aquifer. The model differs from other lumped parameter models by allowing vertical variation in model parameters within cells. The aquifer was divided in five cells corresponding to the watersheds of the creeks supplying recharge. Each cell was treated as a completely mixed tank with a single well selected to represent conditions in that portion of the aquifer. Simulations using historical data from the period 1979 through 1995 showed that the model could accurately reproduce measured water levels and average nitrogen concentrations in the Edwards aquifer and at Barton Springs. The impact of urbanization was simulated by estimating the changes in the hydrology of the creeks supplying recharge. The modeling results suggest that an intense level of development will reduce the average spring flow and significantly increase the average nitrogen concentration in the aquifer.

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1. Introduction

The Edwards aquifer is a karst system lying in a broad arc across central Texas, USA. The portion of the aquifer located just south of the City of Austin is a hydrologically separate system (the darkly shaded area in Figure 1.1), which discharges primarily at Barton Springs. This portion of the aquifer provides drinking water to about 35,000 residents in areas without access to the City drinking water system and provides recreational amenities at Barton Springs Pool, a municipal swimming pool formed by a dam just downstream from the spring. The Barton Springs Salamander, which exists only in the vicinity of the springs, is also dependent on spring discharge for its survival.

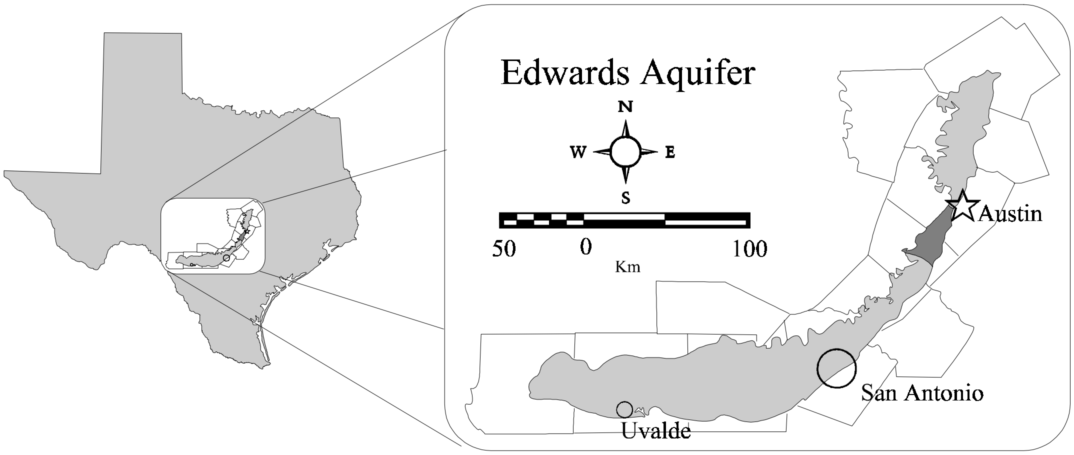

Figure 1.1 Location of the Edwards Aquifer

The long-term protection of Barton Springs is widely considered by residents of central Texas to be a top environmental priority. Urban development is occurring in the watersheds contributing flows to Barton Springs, and there are indications that it may have negatively affected the pristine character of the Springs. The City of Austin has promulgated rules limiting development density and requiring treatment of stormwater runoff from sites within the recharge and contributing zones of Barton Springs to alleviate this potential problem.

The increase of impervious cover associated with urban growth likely will result in changes in the hydrology of creeks contributing to the recharge of the aquifer. The City has undertaken a comprehensive program of stormwater monitoring and modeling to help estimate the potential changes in the hydrology of the watersheds where development is occurring. The goal of the City's surface water model development is the prediction of changes in the surface water systems resulting from specific land use changes in the watersheds.

To estimate the impacts of changes in surface water quality on the Barton Springs portion of the Edwards aquifer, a model is required that can predict the response of the aquifer to varying inputs of recharge quantity and quality. The aquifer is an extremely complex system about which little is known concerning flow paths, travel times, temporal variation in water quality, and other factors crucial to groundwater modeling. This lack of understanding persists despite a relatively intensive monitoring program conducted by the City of Austin (COA), the Barton Springs/Edwards Aquifer Conservation District (BS/EACD), the U. S. Geological Survey (USGS) and others.

1.1 Objectives

The objective of this research is the development of a groundwater model to address the impacts of urbanization of the Barton Springs contributing and recharge zones on the water quantity and quality in the portion of the Edwards aquifer discharging at Barton Springs. Conventional groundwater models are overly complicated for this task given the uncertainties in parameterization and the difficulties associated with estimating changes in recharge characteristics resulting from development. This research proposes a parsimonious approach to modeling flow in a karst terrain. The lumped parameter model developed here significantly reduces the amount of data required for model calibration.

A number of specific tasks were performed to develop this groundwater model. The location and amount of data currently available for model calibration and verification were identified. These data were analyzed to determine the spatial and temporal distribution of water quality and quantity in the aquifer. A computer program was written to implement the mathematical description developed for the aquifer. Aquifer properties were established which allowed model calibration. Data for long-term flow and constituent inputs were generated by estimating changes in diffuse recharge characteristics, surface water flow regimes, and water quality caused by urbanization.

1.2 Significance of Work

The significance of this work lies in three main areas: model development, an increased understanding of the Barton Springs physical system, and the creation of a tool which will allow regulatory agencies to evaluate the impact of urbanization on the aquifer. A new type of lumped parameter model that allows vertical variation within cells is proposed and developed. This type of model should improve predictions in water table aquifers which are strongly stratified, while it retains the simplicity resulting from using lumped parameters.

Analysis of existing water quality data from wells and Barton Springs adds to our knowledge of the current state of the aquifer and the behavior of the system over the last 15 years. Prior to this study, little work had been done to document long-term variation in water quality or the relationship between land use and constituent concentrations. In addition, an extensive analysis of the relationship of water levels to recharge was required to estimate the parameters needed to calibrate the model.

There has been an extensive debate in the Austin area about the potential effects of urban development on water quality at Barton Springs; however, there has never been a method to estimate these impacts. The Texas Natural Resource Conservation Commission declined to impose rules requiring the treatment of stormwater runoff in the Barton Creek watershed because of the lack of a quantifiable relationship between water quality in the creek and in the aquifer. Questions also have been raised about whether the use of septic systems in new residential developments will reduce groundwater quality and if an increase in impervious cover in the contributing watersheds will affect the amount of water recharged to the aquifer.

The proposed groundwater model provides a link between the surface and groundwater systems so that the groundwater effects of changes in water quality and quantity in the creeks can be estimated. The model provides a tool for the regulatory community to investigate the physical impacts of development and to evaluate the effect of water quality and quantity regulations on the Barton Springs portion of the Edwards aquifer. Model simulations based on a scenario of intense development in the areas contributing recharge to the aquifer predict significant changes in water quality and spring discharge.

1.3 Description of Study Area

The Edwards is a complex carbonate aquifer which exhibits numerous karst features, such as caves, sinkholes, and other solution features. The Barton Springs portion of the Edwards aquifer is composed of the Cretaceous-age Edwards Limestone and Georgetown Limestone, which dip generally to the east. It is underlain by the relatively impermeable Walnut Formation and bounded on the west by the Glen Rose Limestone. These rocks yield relatively little water compared to the Edwards. To the east, the water in the Edwards gradually becomes more saline, with the eastern boundary of the aquifer commonly considered to be the line where the concentration of total dissolved solids exceeds 1000 mg/L (approximately coincident with Interstate 35). To the south, a groundwater divide near Onion Creek separates the Barton Springs portion and the southern portion of the Edwards. Figure 1.2 shows the extent of the aquifer in the study area and a typical potentiometric surface. The bold arrows indicate the general direction of water flow.

The Edwards aquifer is under both confined and unconfined conditions. In the eastern portion of the study area, the aquifer is overlain by the Del Rio Clay. These rocks form an upper confining layer to the aquifer; therefore, the Edwards Limestone only outcrops in the western half of the study area. The shaded area in Figure 1.3 shows the 80-square mile outcrop of the Edwards. Although almost half of the aquifer in overlain by the Del Rio Clay, much of this area is under water table conditions. Of the aquifer as a whole, approximately 79% is under water table conditions and 21% is under confined conditions (Slade et al., 1986).

Numerous down-to-the-east normal faults with displacements as great as 200 feet are present within the Barton Springs segment of the aquifer. Abundant caves, sinkholes, and enlarged fractures are evidence of the karst nature of the aquifer. The geology of the aquifer has been described in numerous reports including those by Brune and Duffin

(1983), Rose (1972), Garner and Young (1976), Young (1977), Slade et al. (1986), and the Austin Geological Society (1995).

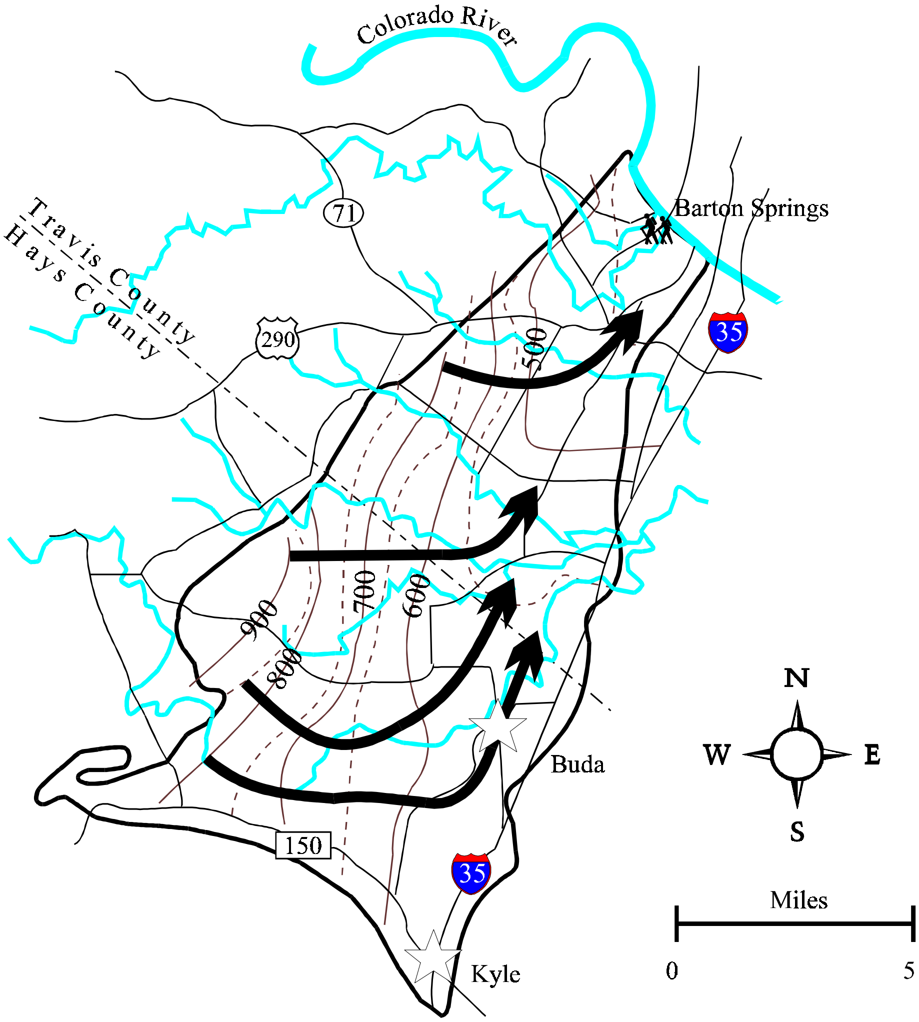

Figure 1.2 Project Study Area (after Slade et al., 1985)

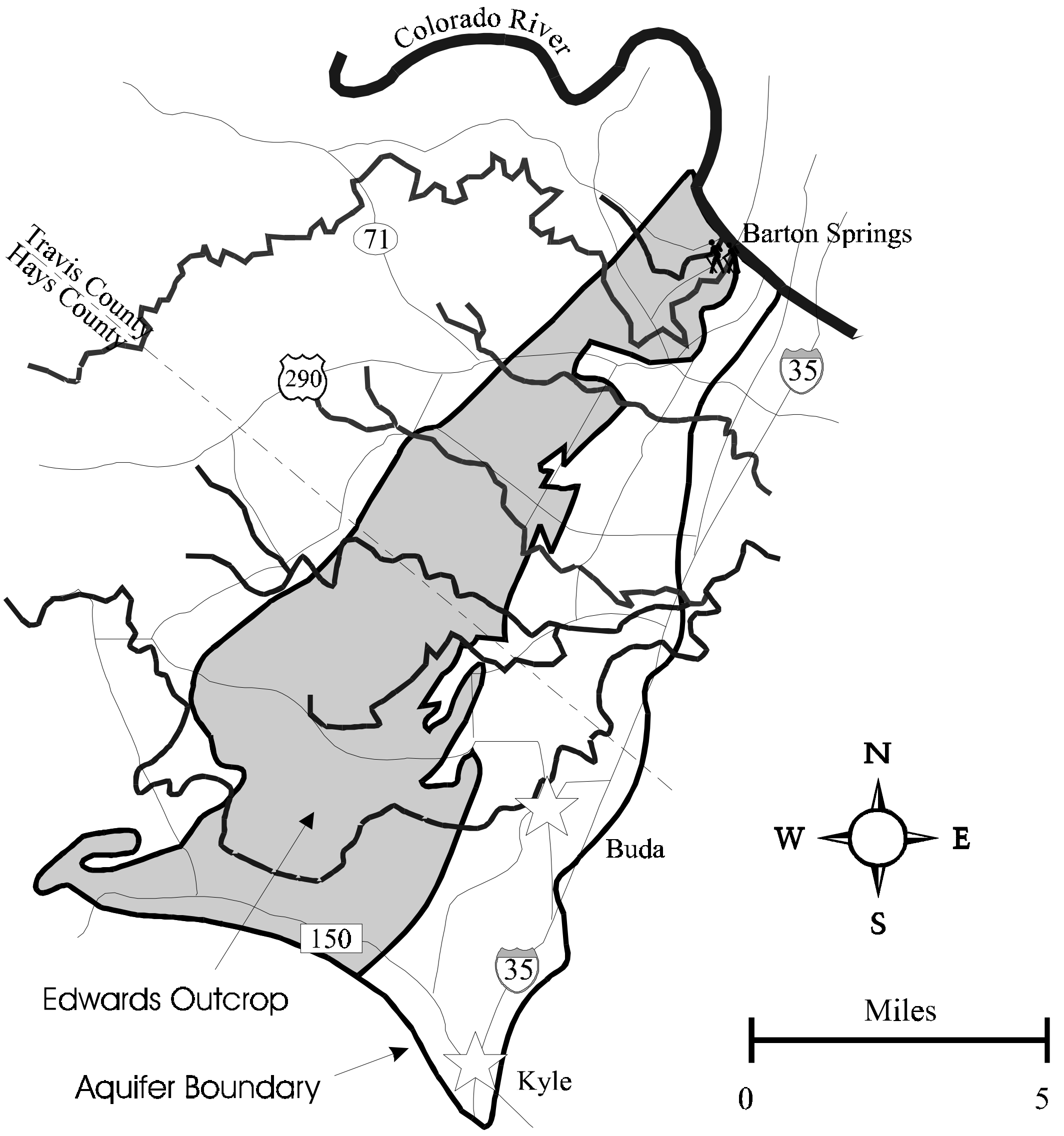

Figure 1.3 Outcrop of the Edwards Limestone in the Study Area

Flow in the aquifer occurs primarily in caves and cavities, and secondarily through porous media. Slade et al. (1986) analyzed caliper and drillers' logs for 79 wells in this area and found evidence of at least one cave or cavity in the saturated zone of the aquifer in 49 of them. Abrupt increases in the discharge of Barton Springs following heavy rains are additional evidence of extensive conduit development in the aquifer. The importance of conduit development to well performance is demonstrated by yields in adjacent wells, which often differ by as much as four orders of magnitude (Slade et al., 1986).

Flow in the aquifer moves from the west toward the east until the edge of the confined portion is reached; there, the flow moves generally northeast to discharge at Barton Springs. The western portion of the aquifer has the highest gradients and the least change in head from low to high flow conditions. Water levels fluctuate less than 10 feet in this area. The eastern portion of the aquifer has the lowest gradients, indicating extensive cavern development. Water levels in wells in the eastern portion of the aquifer are highly correlated with each other and with flow at Barton Springs (Slade et al., 1986). The levels may vary as much as 90 feet with changes in spring discharge.

A small area just to the west of Barton Springs appears to be hydraulically separated from the main portion of the aquifer. Differences in water quality and lack of response of wells to changes in water level in Barton Springs Pool are evidence of this separation (Senger, 1983). This portion of the aquifer discharges at Cold and Deep Eddy Springs and is not included in the study area of this project.

Five main creeks supply most of the recharge to the Barton Springs portion of the Edwards. The watersheds of these creeks are divided into contributing and recharge zones. The contributing zone consists of the portion of the watersheds lying west of the aquifer and underlain by the Glen Rose Limestone. Development in this area will affect the volume and quality of baseflow and direct runoff which enters the creeks. To the east, the creeks flow over the outcrop of the Edwards Limestone, where recharge to the aquifer occurs. This area is termed the recharge zone. Recharge in this area also occurs by direct infiltration of rainfall into the aquifer.

2. Literature Review

Selecting the appropriate model for estimating impacts of urban development and other nonpoint sources of pollution is a major task. An appropriate conceptual model should be sufficiently simple so as to be amenable to mathematical treatment, but it should not be too simple so as to exclude those features which are of interest to the investigation at hand. The information should be available for calibrating the model, and the model should be the most economic one for solving the problem at hand (Bear, 1979).

To completely model a system requires a very detailed knowledge of the physical properties and the processes governing water movement. The virtue of a model rests in its ability to predict a general system from incomplete or partial data. The parsimonious model simplifies the representation of the physical structure and of the processes involved. This is especially appropriate in light of the extraordinary heterogeneity exhibited by karst aquifers.

Numerous types of models have been developed and used to predict water levels and spring discharge from karst aquifers. The simplest are black box models that contain no spatial information, but can predict spring discharge or other aquifer properties. Dreiss (1989) used time moment analysis to relate a time series of inputs (recharge) to a series of outputs (spring flow). Simple regression models also have been used to predict water levels in karst aquifers (Zaltsberg, 1984). The limitation of these types of models is that they lack predictive power.

Deterministic models for groundwater flow and transport may be physically based and may have either distributed or lumped parameters. Lumped models lack the spatial dimension in the equations describing flow and transport; consequently, only ordinary linear differential equations must be solved. These models offer the opportunity to simulate a given system with fewer data requirements for parameterization and calibration than their distributed counterparts. Lumped parameter models in groundwater applications generally have been single cell models such as those developed by Mercado (1976) and Gelhar and Wilson (1974). Karst aquifers also have been modeled as a series of linear reservoirs (Yurtsever and Payne, 1985).

A lumped parameter model for the San Antonio portion of the Edwards aquifer consisting of nine cells was described by Wanakule and Anaya (1993). Because of the large cell size in their model relative to the number and distribution of conduits and other heterogeneities, they were able to represent the aquifer in each cell as a single equivalent porous medium. Lumped parameter models also have been described by Simpson (1988), who termed them discrete state compartment models. Campana and Mahin (1985) used the terminology to describe their 34-cell model of the southern Edwards, which they employed to estimate the groundwater age distribution and aquifer properties.

Distributed parameter models are normally chosen to increase the accuracy of predictions and to achieve a higher degree of spatial resolution. Several distributed parameter models using a single equivalent porous medium have been developed for the San Antonio portion of the Edwards (Maclay and Land, 1988; Thorkildson and McElhaney, 1992), although none perform better than the nine cell model developed by Wanakule and Anaya. The most elaborate of these distributed parameter models was developed by Kuniansky and Holligan (1994) at the USGS. This is a finite element model of the Edwards/Trinity aquifer system containing over 7000 elements. Despite the high degree of spatial resolution, difficulties in generating input data for the model have limited its usefulness.

Dual porosity distributed parameter models also have been developed for karst aquifers (Teutsch and Sauter, 1992). These models generally represent conduit and diffuse flow as separate systems linked by a transfer function. They have the advantage of being able to represent the fast transit and slow depletion often exhibited by karst aquifers, but at the cost of more than doubling the number of parameters required for calibration.

This review of karst aquifer models demonstrates the evolution in model complexity that results from attempts to increase the accuracy of predictions. The general tendency has been to increase the number of cells in the x-y plane while ignoring improvement that might be achieved by incorporating variation in the vertical direction. This approach has not been consistently successful. The more spatially detailed models have been difficult to calibrate and verify. In addition, input data must be developed for each cell; consequently, these models are not used to any great extent by regulatory agencies or other groups.

The goal of this modeling effort is the development of a model which is simple to calibrate and use, and yet achieves a high degree of accuracy. This modeling effort differs from preceding studies by retaining a simple spatial description of the aquifer, but allowing vertical variations in aquifer properties such as specific yield *within* cells. Since the variations are contained within the cell, not all the cells need have the same number of layers. Because water and solute movement within cells is not considered, the model retains the characteristic lack of a spatial dimension exhibited by lumped parameter models. This approach is appropriate for highly stratified aquifers under water table conditions. Caves and other solution features in the Edwards tend to develop at elevations near the water table (Kastning, 1983), so changes in water level may have a greater influence on storage and flow characteristics than do lateral changes.

3. Hydraulic Model Development

Development of a groundwater model requires the identification and quantification of all known sources of recharge and discharge. These inputs and outputs are related to the state of the aquifer (i.e., head distribution) by a mathematical description of the aquifer. In the optimum case, this relationship is based on physical principles describing flow and storage in the aquifer, and model parameters are derived from the aquifer properties. This chapter describes the quantification of the model inputs and the development of a parsimonious, physically based description of the Barton Springs portion of the Edwards aquifer.

3.1 Aquifer Recharge

Water balance studies indicate that flow losses in the creeks crossing the Edwards outcrop (shown in Figure 3.1) are sufficient to supply all the known discharge at springs and well fields. Flow loss studies included manual gauging of stream segments in the recharge zone (Slade et al., 1986) and comparison of hourly flow records of gauging stations located upstream and downstream of the recharge zone on each creek (Meadows, 1994).

All of the creeks except for Barton Creek exhibit similar recharge behavior. Below a threshold flow rate in each creek upstream of the recharge zone, all flow is lost to recharge. Once this threshold is exceeded, the recharge rate remains essentially constant despite the increase in water depth in the creek channel associated with higher flows. A typical relationship between flow and recharge is shown in Figure 3.2 for Onion Creek based on two years of daily data. The relationship was developed by subtracting the daily average flow downstream of the recharge zone from the flow upstream of the recharge zone. The data were edited to exclude days when surface runoff to the creek between the two stations caused the downstream flow to be greater than the upstream flow. The edited data still contain numerous points showing less apparent recharge. This effect is the result of measured flow at the downstream station which may have been

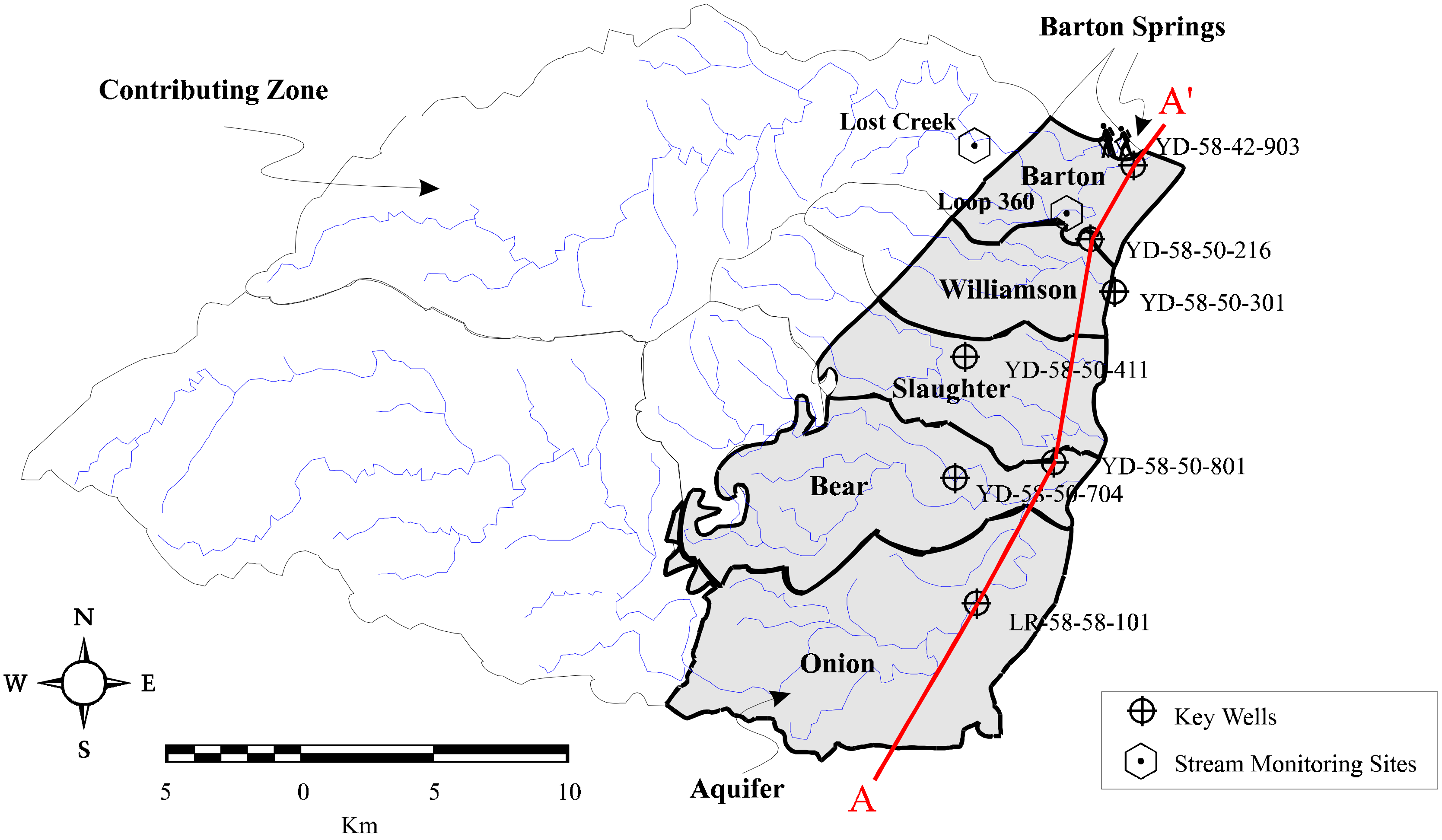

Figure 3.1 Location of Aquifer Cells and Key Wells

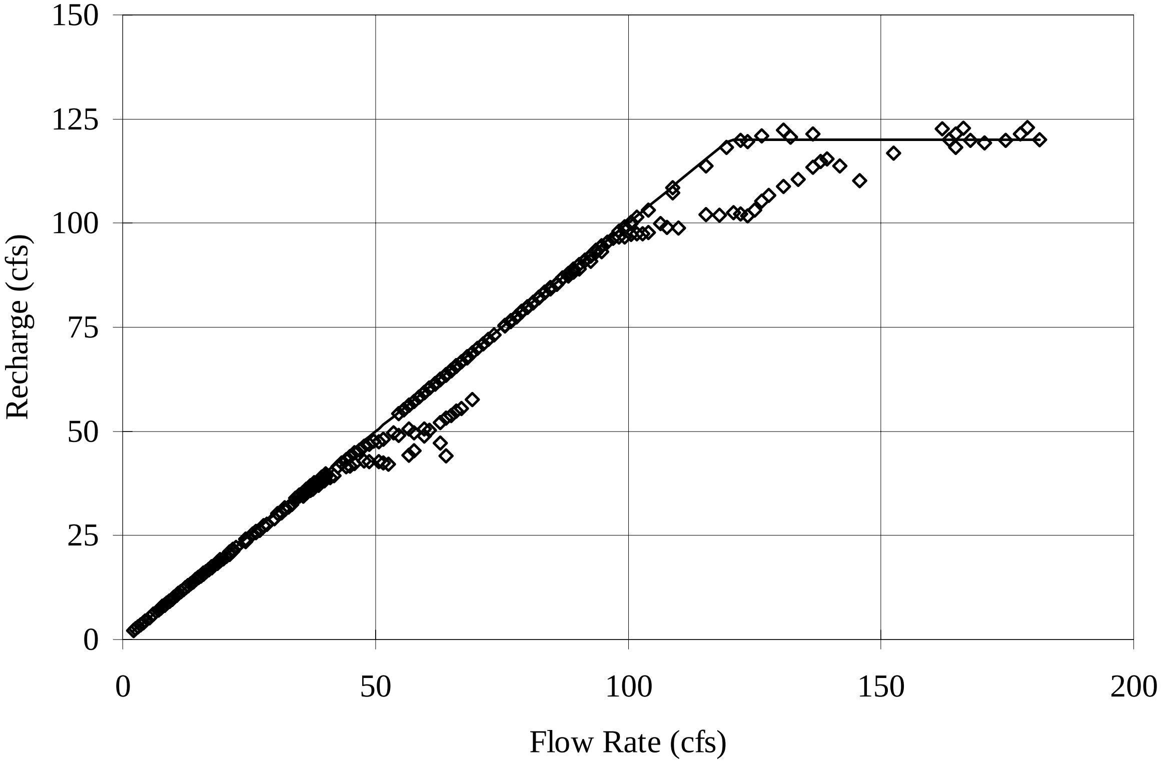

Figure 3.2 Relationship Between Recharge and Flow Rate for Onion Creek

derived from perched water tables near the downstream edge of the recharge zone. Based on the data shown in Figure 3.2, when flow in the creek upstream of the recharge zone is less than 120 cfs, all flow is lost to the aquifer. When higher flows are present in the creek, recharge to the aquifer remains constant at approximately 120 cfs.

Computation of the rate of recharge from Barton Creek is much more complicated than for the other creeks. The elevation of the bed of Barton Creek in its lower reaches (below Loop 360) is at about the same level as the average aquifer level in that location, so that segment of the Creek may either be gaining or losing water depending of the level of the aquifer. Other factors such as the location of recharge features, channel morphology, and geology may also affect the rate of recharge resulting from a given flow rate in Barton Creek.

The rate of recharge in Barton Creek was estimated by comparing the flow rates above the recharge zone at the Lost Creek Boulevard gauging station with the flow at Loop 360 during the period 1989 through 1994 (monitoring locations shown in Figure 3.1). The Loop 360 gauging station is located approximately half-way across the recharge zone. At this location, the bed of the creek is always above the aquifer level, so that recharge above this point should not be significantly affected by aquifer level. Because of the lack of flow data between Loop 360 and Barton Springs Pool, recharge in this section was not considered. The difference between the flow at Lost Creek Boulevard and Loop 360 equals the rate that recharge is occurring in that reach when there is no flow contribution between the stations. The recharge rate is plotted against flow rate at the upstream station in Figure 3.3. The open diamonds represent the difference in the two flow rates. Runoff to the creek between the two stations results in points which plot below the actual recharge rate for a given flow rate. The solid points on the graph represent the recharge assigned to flows greater than 30 ft^3/s.

Several calculated values lie above the line used to define the recharge rate. If these points were valid, the total recharge and estimated spring flow would far exceed measured values. Most of these points are for the first day of storm flow in the creek after an extended dry period. The time lag between the arrival of the flood peak at the two stations, which was not accounted for, may result in the calculation of excess

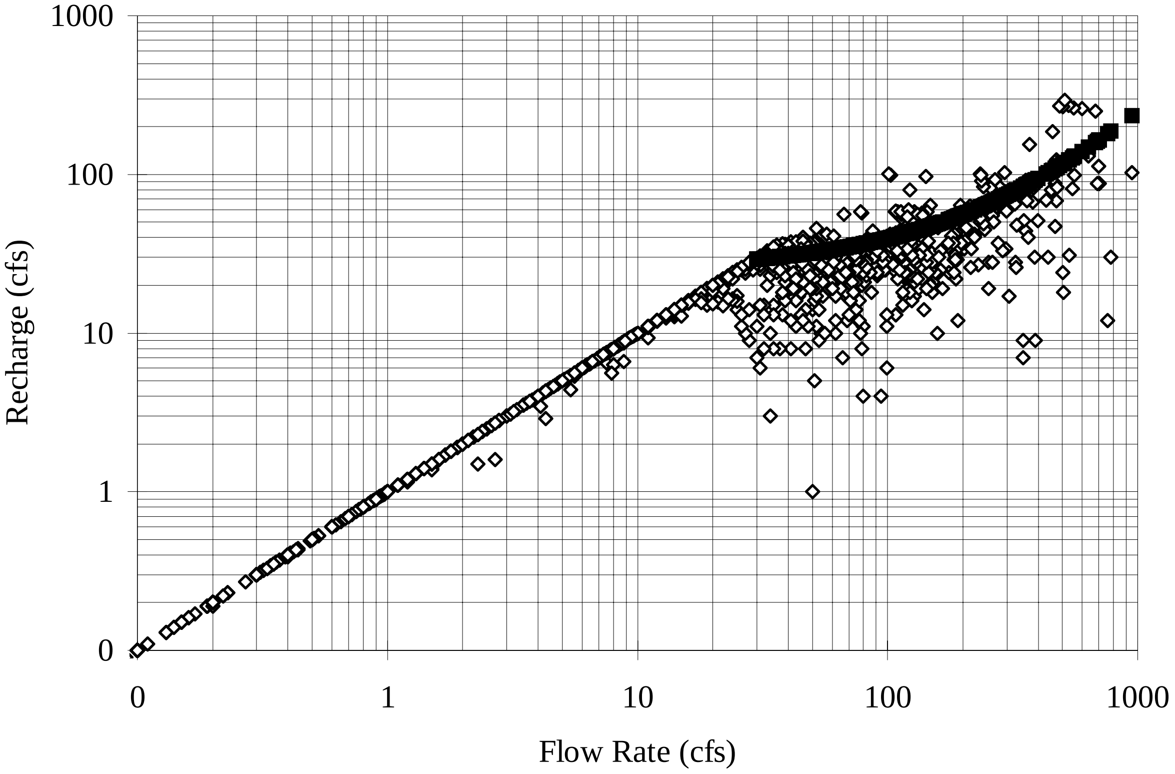

Figure 3.3 Barton Creek Recharge Above Loop 360

recharge. In addition, significant water may be required to saturate the soil and banks during the initial flow and may not reach the aquifer.

The relationship between recharge and flow rate in the creek is similar to that exhibited by the other creeks for flows of less than about 130 ft^3/s. At higher flows, the rate of recharge increases dramatically. The highest recharge rate measured was 250 ft^3/s; this was assumed to be the maximum rate. The increase in the rate of recharge at higher flow rates may be a function of channel morphology, differences in hydraulic conductivity between the base and banks of the channel, submergence of recharge features, or scour during high flow rates which exposes recharge features in the creek bed. To calculate recharge, the following relationship was used:

For $Q_C < 30$ cfs, $Q_R = Q_C$

For $30 < Q_C < 1000$ cfs, $Q_R = -(1\times10^{-8})Q_C^3 + (1\times10^{-4})Q_C^2 + 0.135Q_C + 25.1$

For $Q_C > 1000$ cfs, $Q_R = 250$

where Q_C is the flow rate in Barton Creek at Lost Creek Boulevard (cfs) and Q_R is the rate of recharge (cfs).

Maximum recharge rates in the creeks based on analysis of flow loss data are shown in Table 3.1. Total recharge to the aquifer from the five creeks was calculated for the period 1979 through 1995 based on the flows from the gauging stations upstream of the recharge zone. Surface runoff from the recharge zone to the creeks was not included in the calculations, because significant runoff from these surfaces only occurs during the largest storm events, when the maximum recharge rate has already been reached.

Table 3.1 Maximum Recharge Rates

Creek	**Maximum Recharge Rate (ft^3/s)**
Onion	120
Bear and Little Bear (Total)	66
Slaughter	52
Williamson	13
Barton	250

The percentage of recharge contributed by each creek during this period is shown in Table 3.2. The flow rate of Barton Creek at Lost Creek Boulevard was estimated for the years 1979-1988, so that a longer period of aquifer conditions could be simulated. Estimates were based on (1) the flow measured at other gauging stations on the creek that had flow records overlapping the data at Lost Creek Boulevard or (2) on the flow in Onion Creek when no other records were available. The percentage of recharge contributed by each creek over this longer period was essentially the same as that for the period when actual flow measurements were available at all sites. Total recharge from the creeks for the period 1979-1995 was equal to about 104% of the reported discharge at Barton Springs during the same period. Other discharges from the aquifer include well pumpage (about 10% of discharge from Barton Springs), leakage to other aquifers (ungauged), and baseflow to Barton Creek (ungauged).

Table 3.2 Recharge Contributed by Each Creek

Creek	Average Annual Recharge (ft^3)	% of Creek Recharge
Onion	9.8×10^8	46
Bear and Little Bear	2.8×10^8	14
Slaughter	1.1×10^8	6
Williamson	6.0×10^7	3
Barton	6.3×10^8	31
Total	**2.1×10^9**	**100**

The type of flow in the creek, either baseflow or direct runoff of stormwater, which is recharged is an important factor in determining water quality in the aquifer. The percentage of recharge derived from direct runoff was estimated by assuming that direct runoff occurred on days when the flow was larger than the average flow for the previous day. Table 3.3 shows the results of this analysis. Williamson Creek, which has the most impervious cover, has the largest fraction of its recharge contribution derived from storm flows, whereas Onion Creek, which is the least developed watershed, has the lowest.

Approximately 9% of total creek recharge is derived from storm runoff, based on the relative contribution of each creek and the portion of the recharge in the creek originating as storm flow.

Table 3.3 Amount of Recharge Derived from Direct Runoff

Creek	% Recharge from Storm Runoff
Onion	6
Bear and Little Bear	8
Slaughter	20
Williamson	25
Barton	10

Diffuse recharge was assumed to occur at a constant rate, which is a reasonable assumption when the thickness of the vadose zone is large. Throughout most of the Edwards recharge zone, the water table lies more than 100 feet below the land surface. The average rate of rainfall infiltration was estimated with the Groundwater Loading Effects of Agricultural Management Practices (GLEAMS) model developed by the U. S. Department of Agriculture (Knisel, 1993). Using historical rainfall data from the period 1979-1993 and descriptions of the soil and vegetation types on the recharge zone, average infiltration was estimated to be about 2 in/year, which is about 6% of the average annual precipitation. The daily infiltration was multiplied by the approximate surface area of each cell to calculate the daily volume of infiltration.

Based on the total area of the recharge zone, the yearly volume of water contributed by diffuse recharge is about 3.7×10^8 ft^3. The average total recharge to the aquifer is about 2.5×10^9 ft^3, so diffuse recharge accounts for 15% of the total. This is the same relative proportion estimated by Slade et al. (1986), although they reported different contributions for the individual creeks.

3.2 Aquifer Discharge

Discharge from the Barton Springs portion of the Edwards aquifer occurs mainly from a series of springs in and around Barton Springs Pool, which is located on Barton Creek near its confluence with the Colorado River. Smaller springs, Cold Springs and Deep Eddy Springs, located to the northwest of Barton Springs, are ungauged and hydraulically separated from the main portion of the aquifer and were not considered in this study. Water is also removed from the aquifer by water wells, as baseflow to Barton Creek, and as subsurface flow to other aquifers.

The USGS has developed a rating curve to estimate discharge from Barton Springs based on the water level in well YD-58-42-903, which is located adjacent to the springs. Spring discharge in the model was calculated from the USGS rating curve. The rating curve and best fit line through the measured points is shown in Figure 3.4. The equation for the line shown on the graph is given by:

$$Q_S = 42.88(x - 432.82)^{0.628}$$

where Q_S is discharge of Barton Springs (cfs) and x is the water level in well YD-58-42-903 (ft). This function has a form similar to that which describes discharge from a tank through a submerged orifice. The only difference is in the value of the exponent which would be equal to 0.5 for orifice flow. The constant, 432.82, is the water surface elevation above mean sea level of Barton Springs Pool. This relationship indicates that the pool must be kept at a constant level for accurate estimation of spring discharge.

Wells penetrating the aquifer supply drinking water to approximately 35,000 residents of northern Hays and southern Travis Counties. The monthly pumpage data collected by the Barton Springs/Edwards Aquifer Conservation District were analyzed to determine the location and volumes of the water supply wells. The data from 1994 were the most complete and were used for all years of the simulation. The average pumping rate was about 5 cfs, which is 10% of the long-term average discharge from Barton Springs and equivalent to about 100 gallons per day per capita. Since the time step used

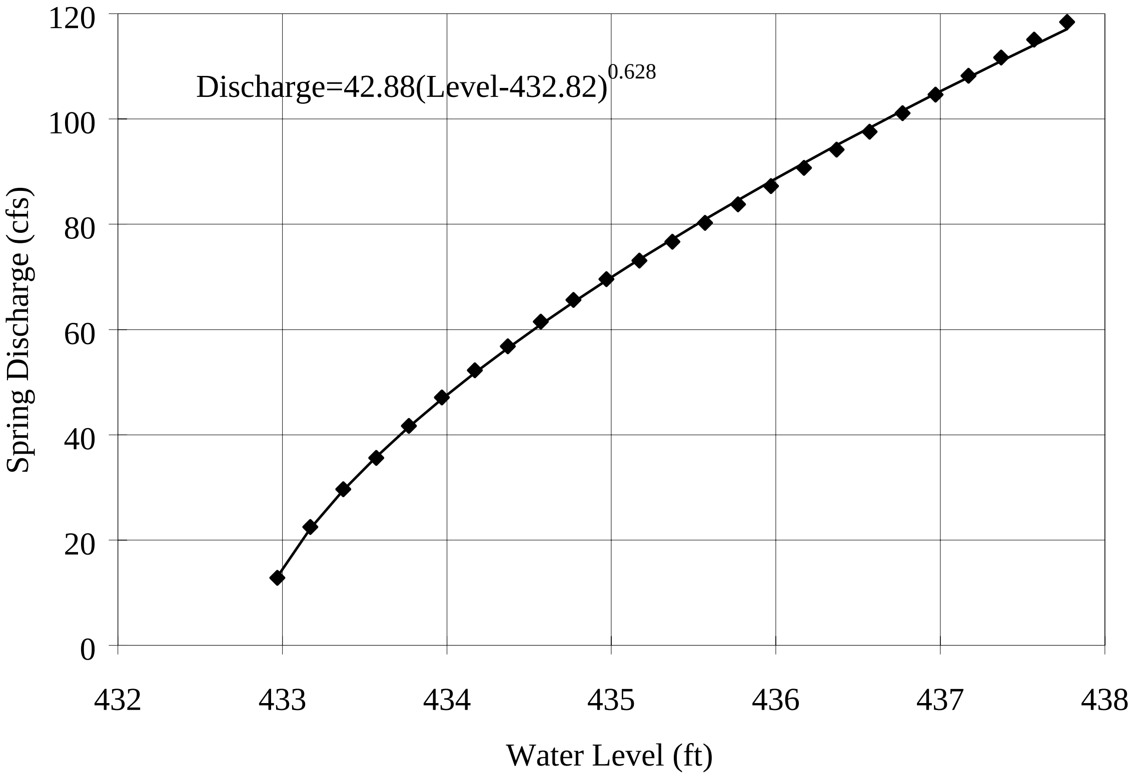

Figure 3.4 Rating Curve for Barton Springs

in the computer simulation was one day, the monthly data were converted to average daily pumping rates and subtracted from each cell during each time step. The greatest volumes are pumped from the Onion and Bear cells, which together account for about 90% of the total. The average daily pumped volumes per cell are shown in Table 3.4.

Discharge from the aquifer also occurs in the segment of Barton Creek between Loop 360 and Barton Springs Pool during periods of high aquifer water levels. The volume and rates of discharge are unknown. Since the recharge from the creeks was larger than the discharge from Barton Springs and known wells, the discharge to the Creek was used as a calibration parameter to improve the spring flow prediction.

Table 3.4 Estimate of Current Pumping

Cell	Average Daily Volume (ft^3)	% of Pumped Volume
Onion	180,000	47
Bear	170,000	44
Slaughter	13,000	4.0
Williamson	9,400	2.5
Barton	9,400	2.5

Slade et al. (1986) concluded that subsurface flow between the Edwards and other aquifers is not significant; however, a study by LBG-Guyton Associates (1994) reported that some of the recharge from Onion Creek flows south to the San Antonio portion of the Edwards aquifer. The volume of water and flow rates are unknown and were assumed to be insignificant for the purposes of this study; therefore, all recharge from Onion Creek was directed to the Barton Springs portion of the aquifer. Subsurface flow to other aquifers also was assumed to be insignificant, so no flow was allowed across the external model boundaries.

3.3 Model Structure and Calibration

The goal of this modeling effort is the prediction of the regional impacts of nonpoint source pollution arising from urban development in the Barton Springs contributing and recharge zones. The impacts are expected to be widespread and lack the local expression which would be characteristic of chemical spills, leaking landfills, or other point sources of pollution. Spatially detailed water quality data are not available at this time, suggesting that a lumped parameter model with a relatively large cell size is the appropriate choice for modeling the Barton Springs portion of the Edwards aquifer.

For most groundwater modeling efforts, a model with a fixed structure is selected and then the parameters are chosen through the process of calibration to achieve the best fit with measured data. In this case, a number of different model structures were evaluated and in each case parameters were selected to achieve the best possible calibration. Variations in model structure included using equations describing turbulent flow in conduits (as an alternative to Darcy's law), changing the number of "layers" in individual cells, increasing the number of cells, allowing discharge to occur across the southern boundary of the model, and letting hydraulic conductivity vary with elevation. Allowing vertical variation in aquifer properties within cells resulted in the best predictions. Since the variation occurs within cells, each cell may have a unique number of "layers." From a practical perspective, the cells with the largest volumes dominate the behavior of the system, so only these cells include multiple layers. A schematic diagram of the final model is shown in Figure 3.5.

The model developed in this study is similar to that developed by Wanakule and Anaya (1993), in that relatively few cells are used to describe the aquifer (only five cells to describe an aquifer covering about 150 square miles), which simplified calibration of the model. The response of individual wells to recharge events supports the validity of large cell sizes. Wells located miles from creeks providing recharge to the aquifer exhibit rapid increases in water levels simultaneously with wells near the creek beds. The Barton Springs portion of the Edwards aquifer receives the bulk of its recharge from the five main creeks which cross the recharge zone. These creeks are fairly evenly spaced, which suggested the use of a five-cell model to predict the behavior of the aquifer.

A single well was chosen in each cell to represent conditions in that portion of the aquifer. The well chosen to represent the conditions in the Barton cell (YD-58-42-903) is

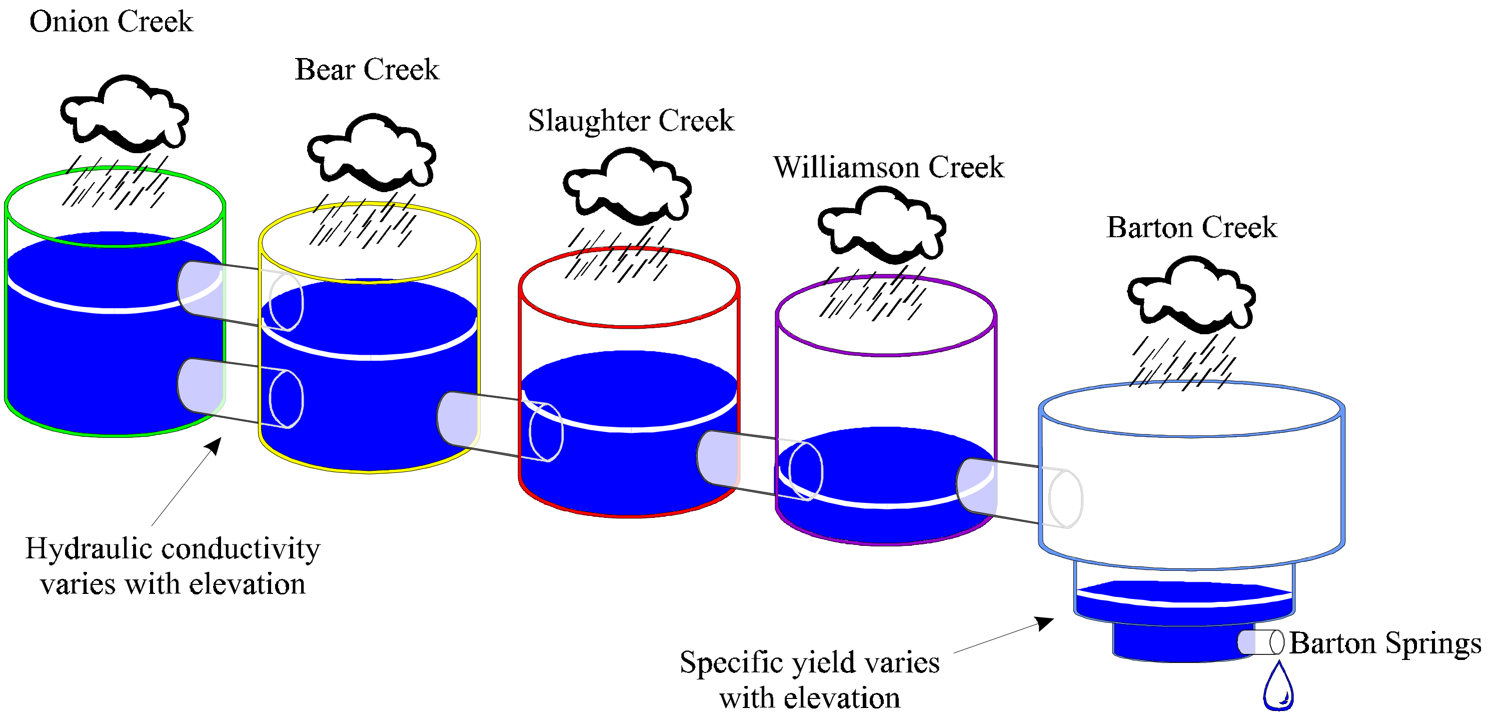

Figure 3.5 Schematic Diagram of the Barton Springs Model

located adjacent to Barton Springs and is used by the USGS to estimate spring discharge. The wells chosen in the other cells are located along the eastern portion of the aquifer. This is the area that experiences the maximum range of groundwater elevations (up to 90 feet). Each cell is treated as a tank which is assigned an effective area (equivalent to the product of specific yield and surface area). Currently, there is no well appropriately located in the Slaughter cell with sufficient measurements to calibrate against. The locations of the cells and key wells used in the study are shown in Figure 3.1, and a cross-section through a number of the key wells is shown in Figure 3.6.

There are a number of significant differences between this model and previous karst models, including the tank model developed by Wanakule and Anaya (1993). Rather than increasing the number of cells to obtain better simulated results, model predictions were improved by allowing vertical variation of aquifer properties within cells. In particular, specific yield and hydraulic conductivity of the cells are functions of elevation. A short time step (daily) was used in the model, which facilitated the calculation of recharge, increased the accuracy of the model, and allowed the governing equations to be solved explicitly. In addition, a simple method of calculating recharge from creek flow upstream of the recharge zone was developed, which allowed more accurate estimates of recharge than many of the other Edwards' models that use monthly time steps.

Accuracy of the model was judged using several criteria. One of the primary tests was the accuracy of model predictions for both spring discharge and water surface elevations during fall 1979. Barton Spring discharge data and numerous water level measurements for a number of the key wells used in the model were available for that time period. To determine aquifer properties during periods of extreme water levels, data from the period 1989 through 1994 were used. The most important criteria used to judge model accuracy during this period was spring discharge and water surface elevations in the cells most distant from the springs. Daily water level measurements for key wells in these cells were available for much of this period. The best fit was determined by comparing the sum of the squared error for water level and spring flow.

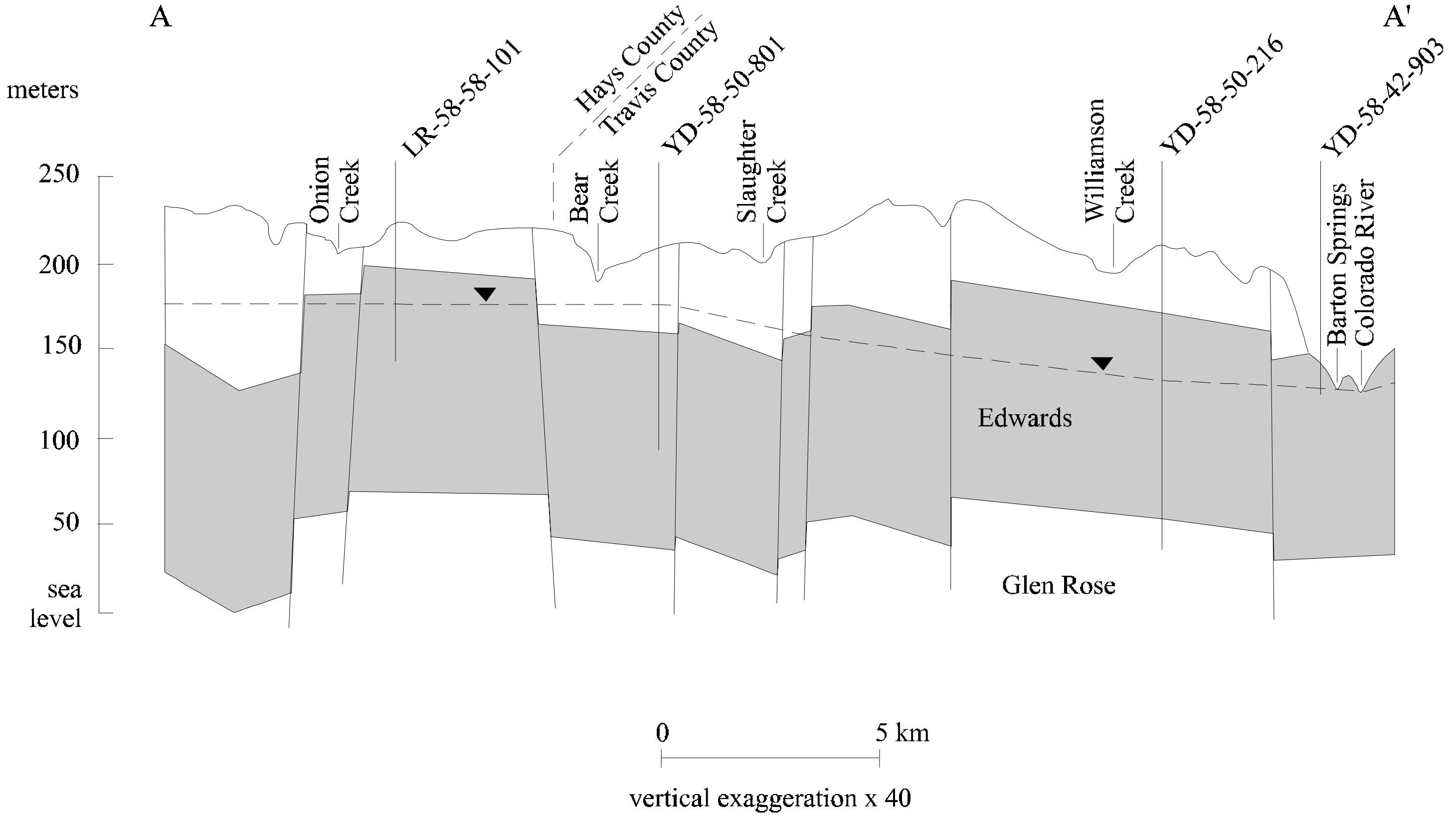

Figure 3.6 Cross-Section through the Edwards Aquifer

Development of Flow Equations

Darcy's law is normally used to describe groundwater flow; however, flow in the Barton Springs portion of the Edwards aquifer occurs primarily in caves and cavities and secondarily through porous media. The use of Darcy's law is appropriate only for the description of laminar flow in the subsurface (i.e., flow characterized by a small Reynolds number). The onset of turbulent flow in conduits generally occurs at a Reynolds number of approximately 2000. Dye released in a well about 200 feet south of Barton Springs was first detected in discharge about 10 minutes after injection, a velocity equivalent to 29,000 ft/d (Slade et al., 1986). This velocity, combined with a conduit "diameter" on the order of one foot, results in a Reynolds number which far exceeds the threshold value for the onset of turbulent flow. The recognition of widespread caves and other conduits for flow suggested that laminar flow was not the appropriate formulation.

The original model consisted of five cells arranged linearly and connected schematically with segments of pipes representing conduit flow. The Chezy-Manning equation shown below was used to describe turbulent flow in the connecting pipe segments:

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

where Q is the discharge (ft^3/s), A is the area of the pipe (ft^2), R is the hydraulic radius (area/wetted perimeter), and S = Slope of the total head ($\Delta H/L$). Because of the large number of unknowns on the right hand side of the equation associated with descriptions of the conduits, the expression can be simplified to:

$$Q = K \Delta H^{1/2}$$

where $$K = \left(\frac{AR^{2/3}}{nL^{1/2}} \right)$$

Predictions of flow rates at Barton Springs using this formulation were very accurate and supported this conceptual model; however, calibration of the model to accurately reproduce measured heads in the individual cells was not successful. During periods of recharge, predicted water levels in the aquifer far exceeded (by hundreds of feet in some cases) measured values.

The final model describes flow between the cells using Darcy's Law. The hydraulic conductivity was assigned to the boundaries between cells, which was the method employed by Prickett and Lonnquist (1971), rather than to the centroid of each cell in the manner of Trescott et al. (1976). The saturated thickness of the upstream cell was used to calculate the transmissivity. All external model boundaries were treated as no-flow boundaries, so there are only four boundaries where flow occurs. Flow rate across each internal boundary was calculated as:

$$Q_G = Kwb(\frac{\Delta h}{l})$$

where Q_G is the groundwater flow rate across the boundary, w is the width of the boundary, Δh is the head difference across the boundary, b is the saturated thickness of the upstream cell, and l is the distance between the key wells in each cell. This was simplified in the model to:

$$Q_G = K' b\Delta h$$

where

$$K' = \frac{Kw}{l}$$

A reasonably good prediction of water levels in each of the cells could be obtained using this formulation; however, the model consistently over-predicted the water levels in the Onion cell during periods of peak recharge and high aquifer levels. The slope of the predicted recession curve closely matched the observed recession, indicating that the parameter value describing cell storage was fairly accurate. By increasing the hydraulic conductivity of the cell boundary as the water level increased, water moved out of the cell at a faster rate, and the slope of the recession was largely unaffected. This change also resulted in better water level predictions in the adjoining Bear cell. A simple two-layer representation of the hydraulic conductivity was sufficient to reproduce the measured water level fluctuations. A process of trial and error lead to the choice of 600 feet above mean sea level in the key well as the boundary between zones of different conductivity. The following equation was used to describe flow between the Onion and Bear cells when the water level exceeded this threshold value:

$$Q_G = K_l^{'}(350)(\Delta h) + K_u^{'}(h - 600)(\Delta h)$$

where $K_l^{'}$ and $K_u^{'}$ are the flow proportionality constants for the lower and upper sections, 350 feet is the distance between the base of the cell and an elevation 600 feet, h is the head in the Onion cell, and Δh is the difference in water level elevations between the Onion and Bear cells.

Development of Aquifer Storage Parameters

Since each aquifer cell is treated as a tank, a parameter is required to relate fluctuations in water surface elevation to changes in the amount of water in the cell. This parameter is described as the effective area of the tank and is physically equivalent to the product of the average specific yield and surface area of the tank. The effective area of each cell was chosen to reproduce the spring flow recession and associated drop in aquifer water levels which occurred between August 1979 and January 1980. This is the same period chosen by Slade et al. (1985) for the calibration of their model.

The relationship between water level at the beginning of each time step and water volume is described by:

$$h = \frac{V}{A} + \zeta$$

where *h* is the water surface elevation of the cell, *V* is the volume of water in the cell, *A* is the effective area of the cell, and ζ is the elevation of the base of the cell above mean sea level.

If each of the cells had a specific yield independent of elevation, one would expect that the spring flow recession would be more rapid at the beginning. The data clearly demonstrate that the recession is not as rapid when the discharge from Barton Springs is greater than about 75 cfs. Several configurations were tested to reproduce this behavior. The most successful was the division of the Barton Creek cell into three zones. The effective area was assumed to take the form of a step function, assuming three discrete values. The elevations where these values change were estimated during the calibration process and have the physical representation of geologic layers with different specific yields.

The basal zone was defined to include the interval from the bottom of the aquifer (estimated to be about 350 feet above mean sea level) to a measured elevation of 435.26 feet in the representative well for that cell (which corresponds to a Barton Spring discharge of 75 cfs). This interval was assigned a smaller effective area, which produced a more rapid spring flow recession.

A third zone in the Barton cell was defined based on the aquifer response to recharge when Barton Springs is discharging at fairly high flow rates. When Spring discharge exceeds about 110 cfs, additional recharge causes very little increase in water level in the well representing the Barton cell. To reproduce this behavior, a third zone with a higher effective area was required. The base of this zone was determined to be at an elevation of 437.3 feet in the key well (corresponding to a spring discharge of 110 cfs).

The water volume which could be contained in the two lower sections when full was calculated. Since the volume in the cell is known, the layer containing the water surface is also known and the elevation can be calculated as:

$$h = \frac{V_t - \sum_{j=1}^{i-1} V_j}{A_i} + \zeta_\iota$$

where h is the water surface elevation in the Barton cell, V_t is the total water volume in the cell, V_j is the volume of the layers below the layer containing the water surface elevation, A_i is the effective area of the cell layer containing the water surface, and ζ_i is the elevation of the base of the cell layer containing the water surface.

Baseflow Discharge to Barton Creek

During periods of high water levels in the aquifer, numerous ungauged springs supply baseflow to the section of Barton Creek between Loop 360 and Barton Springs. In the model, no baseflow was assumed to occur when aquifer levels were below that necessary to produce some arbitrary rate of discharge from Barton Springs. A minimum discharge from Barton Springs of at least 80 cfs for baseflow to occur resulted in the best calibration. When the predicted flow exceeded that rate, the following equation was used to estimate discharge to the creek:

$$Q_B = 0.6 \times (Q_S - 80)$$

where Q_B is the baseflow discharge to Barton Creek and Q_S is the predicted discharge from Barton Springs.

There is little actual data to confirm or deny this relationship, since spring discharge above the pool has been measured on only two occasions. On 5/29/80 the USGS reported an increase in flow in the lower section of creek of about 4 cfs when Barton Springs was discharging 77 cfs. The BS/EACD measured a discharge to the creek of 2.5 cfs during June 1991, when spring flow was about 90 cfs. The computer simulation of the aquifer for the period 1979 through 1995 predicted that the average discharge to the creek was equal to about 6% of the predicted average spring discharge.

Equations Describing Mass Balance

The model calculates aquifer state based on a daily mass balance for each cell. Each cell is treated as a control volume to which the Reynolds transport theorem is applied. For a conservative substance, this theorem reduces to:

$$\frac{dV}{dt} = I(t) - Q(t)$$

where dV/dt is the change in volume, $I(t)$ is the inflow and $Q(t)$ is the outflow from the control volume (Chow et al., 1988). Inflows to each control volume include creek recharge, diffuse recharge, and flow from adjacent cells. Outflows include well withdrawals and discharge to adjacent cells. For the purposes of calculating diffuse recharge volumes, the surface area of each cell is assumed to conform to the boundaries of the surface watershed of the creek supplying recharge to that portion of the aquifer. Because of the relatively short time step, the integration is done explicitly using Euler's method.

The volume of each cell at the end of each time step except for Barton is calculated by rearranging the Reynolds transport equation to derive the following equation:

$$V_{t+\Delta t} = V_t + S \times (q_i) \times \Delta t - P_{t+\Delta t} + \Delta t \times \sum Q_G \Big|_{t+\Delta t}$$

where $V_{t+\Delta t}$ is the volume of water in the cell at the end of the next time step, V_t is the volume at the end of the preceding time step, Δt is the length of the time step, $\sum Q_G$ is the net groundwater flow rate into the cell from adjacent cells, S x (q_i) is the surface area of the cell times the rainfall infiltration rate, and $P_{t+\Delta t}$ is the volume pumped from the cell during the time step.

The mass balance for the Barton cell is calculated in a similar manner to that of the other cells except that terms expressing the volume of discharge at Barton Springs and baseflow to Barton Creek are included. The following equation is solved at every time step:

$$V_{t+\Delta t} = V_t + \Delta t \times \left(Q_W - Q_B - Q_S\right)\Big|_{t+\Delta t} + S \times (q_i) \times \Delta t + P_{t+\Delta t}$$

where Q_W is the flow from the Williamson cell, Q_B which is the rate of baseflow discharge to the creek, and Q_S is the rate of Barton Spring discharge.

The equations which make up the model were incorporated into a FORTRAN program so that simulations could be run on a computer. The model code and user's guide are contained in Appendix A.

Calibration Results

A comparison of measured and predicted spring discharge during the recession period in fall 1989 is shown in Figure 3.7, and a comparison of predicted and measured water levels in selected wells is shown in Figure 3.8. The predicted water levels are more accurate in the cells most distant from Barton Springs. A good match between beginning and ending water levels in the cells together with the prediction of spring discharge indicate that storage in the aquifer has been accurately estimated.

The spring flow recession from this period was used to estimate the calibration parameter values during periods when spring discharge is between 95 cfs and 40 cfs. Historical flow data from Barton Springs indicate that the discharge varies between approximately 130 cfs and 10 cfs. To extend the range of flows that the model can accurately predict, the period from January 1989 through September 1994 was chosen for final model formulation and calibration. During this period, discharge from the springs varied between about 130 cfs and 18 cfs. This period was chosen not only for the wide range of flows, but because actual flow data for each of the creeks supplying recharge to the aquifer were available.

The measured and predicted discharge from Barton Springs for the calibration period is shown in Figure 3.9. Since the prediction of Barton Springs discharge is based on the water level in the well used by the USGS for flow estimation, the figure also indicates the accuracy with which water level in that portion of the aquifer is predicted.

The erratic reported spring discharge for the winter and spring of 1992 was the result of a large flood in December 1991, which resulted in Barton Springs Pool being drained for repairs. The lower water level in the pool caused the discharge from the

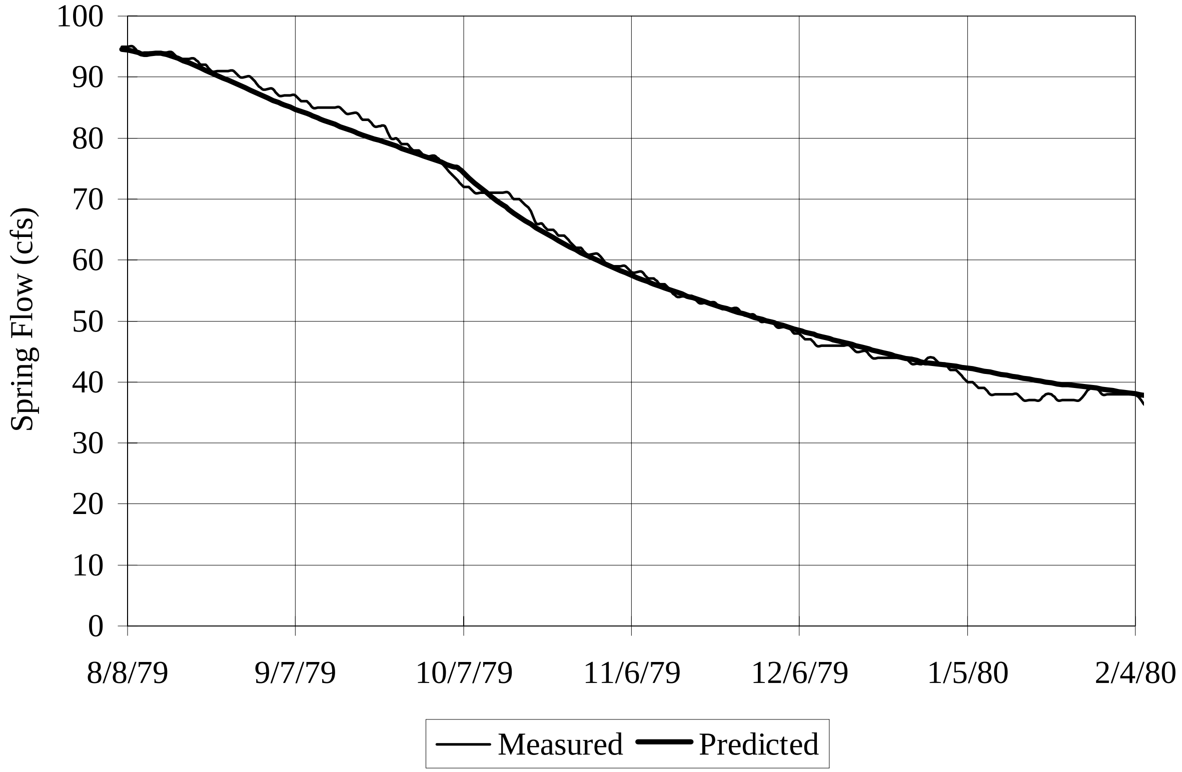

Figure 3.7 Comparison of Spring Flow Recession

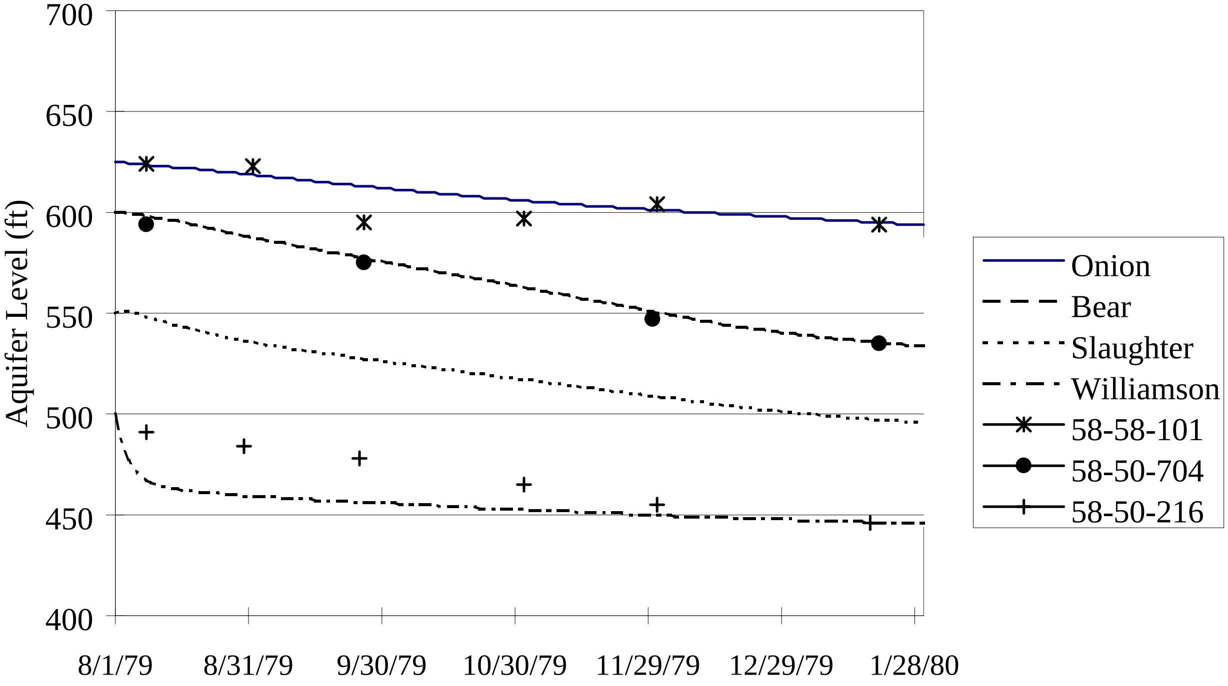

Figure 3.8 Measured and Predicted Water Levels during Recession Period

springs to be underestimated because of its effect on the level in the well used to predict spring flow. Several large storms during the spring of 1992 filled the pool, resulting in large apparent increases in spring discharge. The pool was refilled in the summer of 1992 and accurate discharge estimates were again available. The data from this seven-month period were not included in the calculation of model error during the calibration process.

The flow model was verified by comparing the predicted and measured spring discharge for the period from 8/79 through 1/88. Flow data for Barton Creek at Lost Creek Boulevard were not available for this period, so flow was estimated on the basis of reported data from other stations on Barton Creek (Camp Craft Rd. and Highway 71) and Onion Creek (FM 150). A comparison of predicted and measured values for this period is shown is Figure 3.10.

The representative well for the Onion cell (LR-58-58-101, Franklin) has numerous recorded water level measurements during the simulation period. In addition, the Barton Springs/Edwards Aquifer Conservation District (BS/EACD) installed monitoring equipment on that well in 1991 to record daily water level measurements. A comparison of predicted and measured water levels for the period from 1979 through 1989 is shown in Figure 3.11, and a comparison of predicted and reported daily water levels for the period 5/91 - 9/95 is shown in Figure 3.12. A comparison of measured and predicted water levels for the other cells is contained in Appendix B.

The final calibration parameters for each cell are shown in Table 3.5 and Table 3.6. The choice of the representative well in each cell strongly affects the degree to which the parameters represent a measurable physical property. For instance, the well chosen for the Barton cell is located adjacent to Barton Springs. The proximity to the springs means that the range of water elevations recorded in the well is small (about 5 feet) compared to the range measured in other parts of the aquifer being represented by the cell.

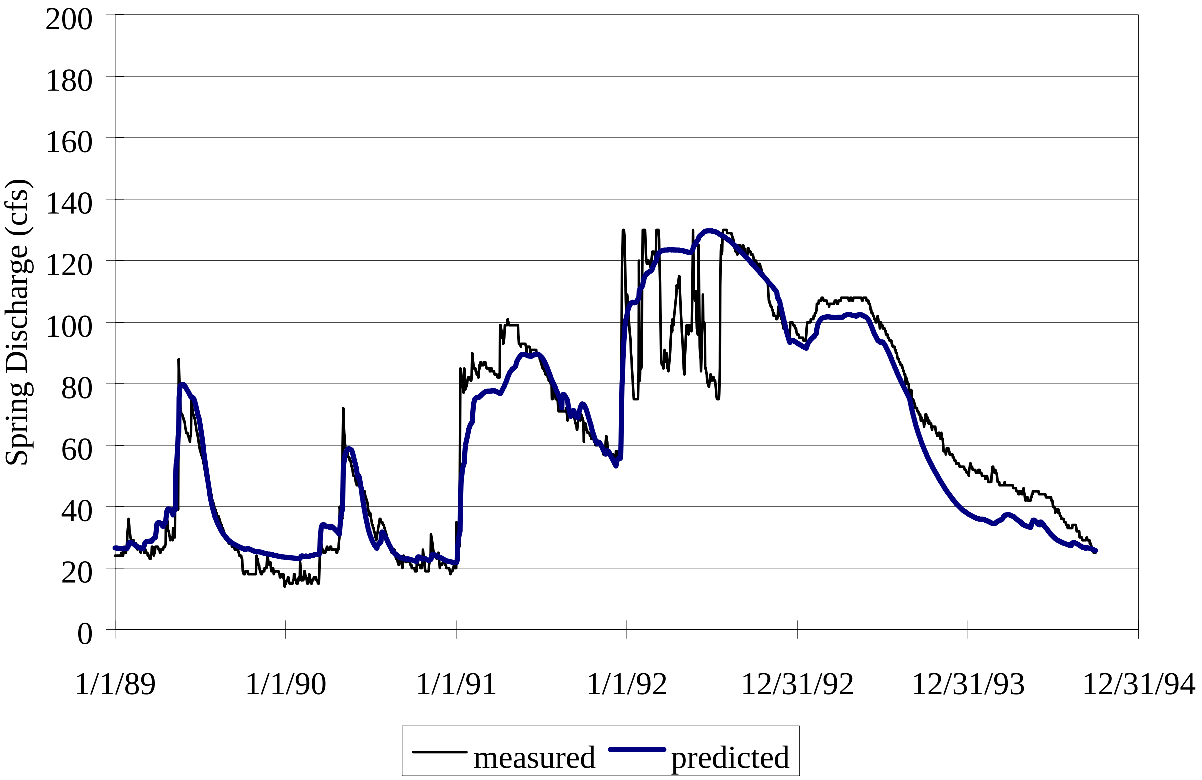

Figure 3.9 Measured and Predicted Discharge for Calibration Period

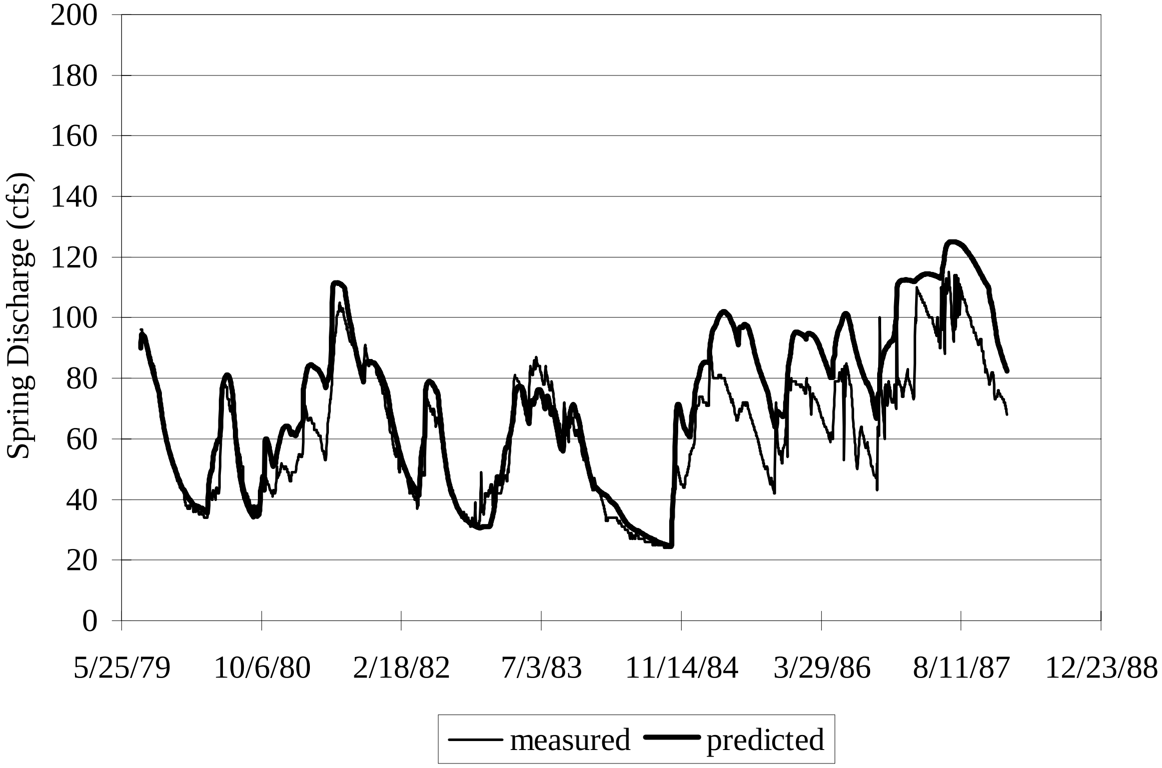

Figure 3.10 Measured and Predicted Discharge for Verification Period

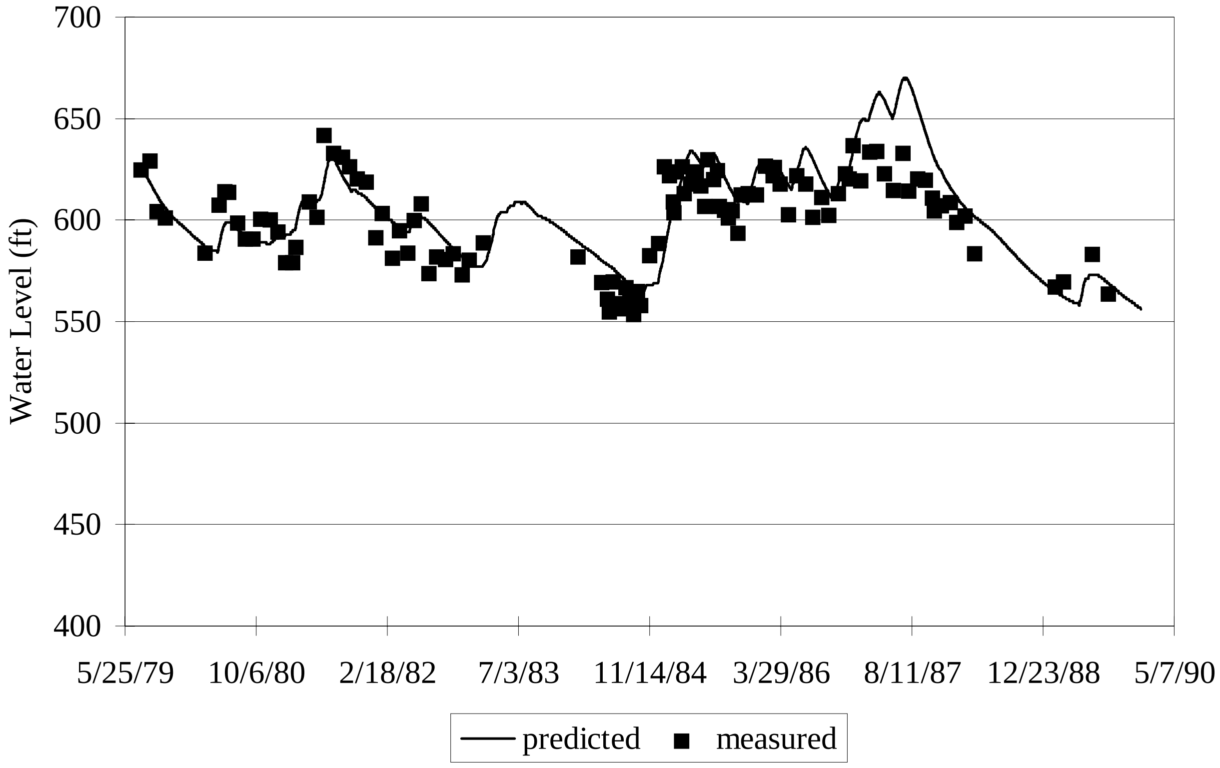

Figure 3.11 Water Levels in Onion Cell near Buda, Texas

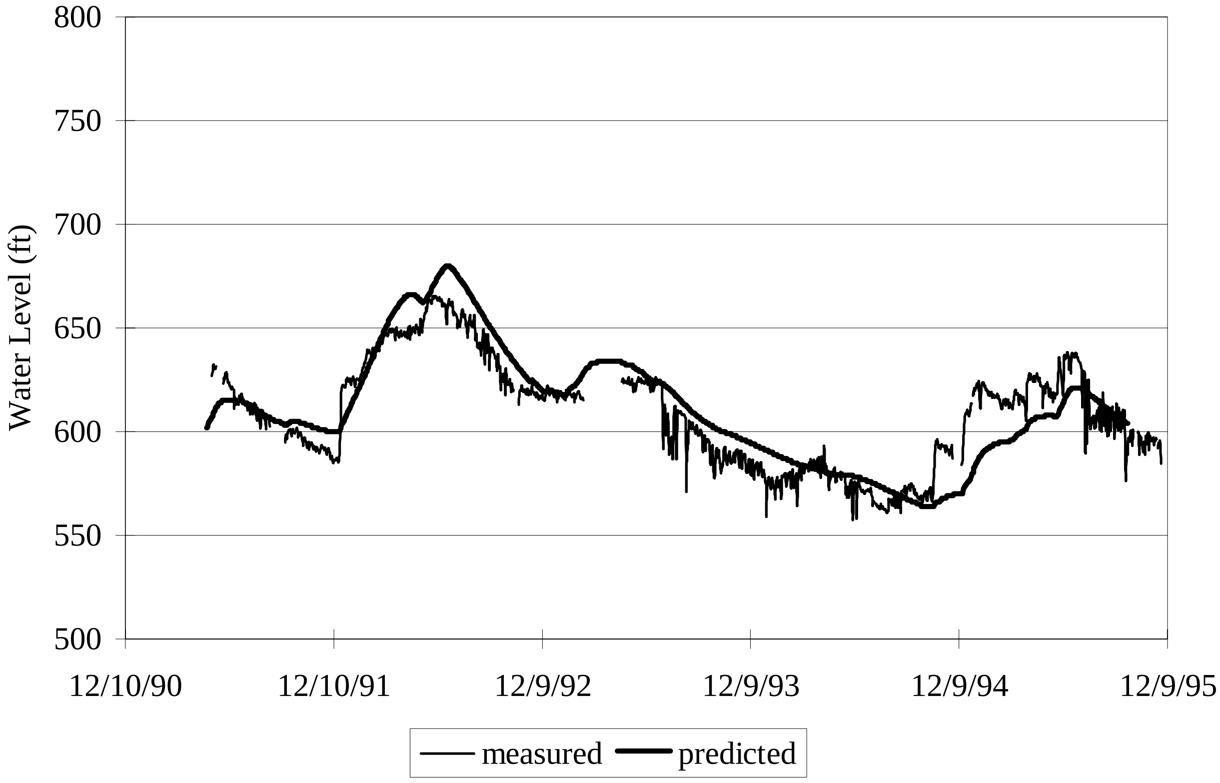

Figure 3.12 Comparison of Measured and Predicted Daily Water Levels in Onion Cell

Table 3.5 Characteristics of the Five Aquifer Cells

Cell	Interval (Feet above msl)	Effective Area (ft^2)	Actual Area (ft^2)	Specific Yield (%)
Onion	250 and above	12,700,000	1,485,000,000	0.9
Bear	250 and above	2,326,000	1,056,000,000	0.2
Slaughter	250 and above	1,434,000	758,000,000	0.2
Williamson	200 and above	1,223,000	557,000,000	0.2
Barton	350 - 435.26	31,207,000	465,000,000	6.7
	435.26 - 437.3	80,000,000		17.2
	437.3 and above	400,000,000		86.0

The small increases in water level resulting from large volumes of recharge mean that the effective area of the cell must be large. If one were to divide the effective area by the surface area of the Barton Creek watershed over the aquifer, the apparent specific yield would be extremely high. Conversely, the wells chosen to represent conditions in each of the other cells were located in the eastern portion of the aquifer, where the range of recorded water levels is fairly large (up to 90 feet). Therefore, a relatively small effective area produces the large changes in observed water level. If the effective area of these cells is divided by the surface area of the corresponding watersheds, the apparent specific yield is very low. The properties of the boundaries between cells are shown in Table 3.6. The parameter labeled “Flow Length” is the distance between the key wells in each cell and is used to calculate the hydraulic gradient between cells.

Table 3.6 Properties of the Boundaries Between Cells

Cell Boundary	Boundary Width (ft)	Flow Length (ft)	Hydraulic Conductivity (ft/d)
Onion/Bear (250-600)	52,800	23,800	40
Onion/Bear (>600)	52,800	23,800	830
Bear/Slaughter	42,200	16,900	115
Slaughter/Williamson	34,800	16,900	120
Williamson/Barton	21,120	12,700	520

3.4 Sensitivity Analysis

A sensitivity analysis was performed to determine the stability of the model predictions given the uncertainty in the estimate of model parameters. The effect of changing the hydraulic conductivity and the effective areas of the tanks were determined separately. Model simulations were performed using values 20% above and below the estimated optimum values.

The effect of variation in hydraulic conductivity was estimated by comparing model predictions of water level and spring discharge during the period of spring flow recession in fall of 1979, water levels in the Onion cell between 1991 and 1995, and spring discharge for the original calibration period of 1989 through 1994. The measured and predicted values for spring flow during fall of 1979 are shown in Figure 3.13. In this case, there are clear differences between the predictions generated with the less than optimum parameter values. When the hydraulic conductivity is uniformly increased by 20%, predicted spring discharge consistently exceeds the measured values. Conversely, a lower hydraulic conductivity greatly reduces the predicted spring discharge.

A comparison of the measured and predicted water levels in the Onion cell is shown in Figure 3.14. Decreasing the hydraulic conductivity has the expected effect of increasing the predicted water levels in the cell, whereas increasing the hydraulic conductivity reduces the predicted water levels. The effect of these changes on spring flow for the period 1989 through 1994 is shown in Figure 3.15. For most of this period, the difference between the predictions is indistinguishable. This is because substitution of a lower hydraulic conductivity in the model increases the average predicted gradient, resulting in essentially the same predicted value for spring discharge. The error in spring flow prediction is only evident during the recession period because the water levels in each of the cells is specified as an initial condition. Since improvement in the prediction of any single variable can be achieved at a cost of increasing the error in another part of the model, the selection of the “optimum” parameter values is an arbitrary process depending on the amount of error which is acceptable for any particular prediction.

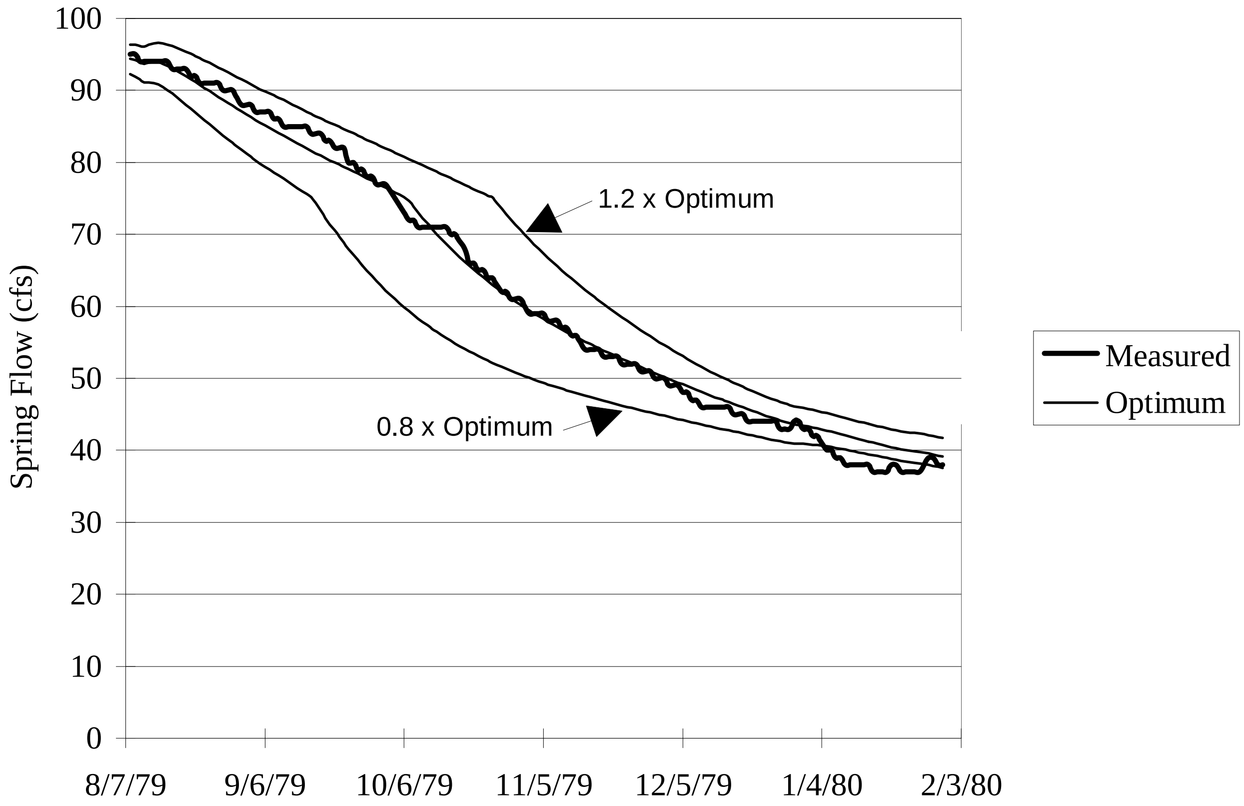

Figure 3.13 Sensitivity of Recession Curve to Hydraulic Conductivity

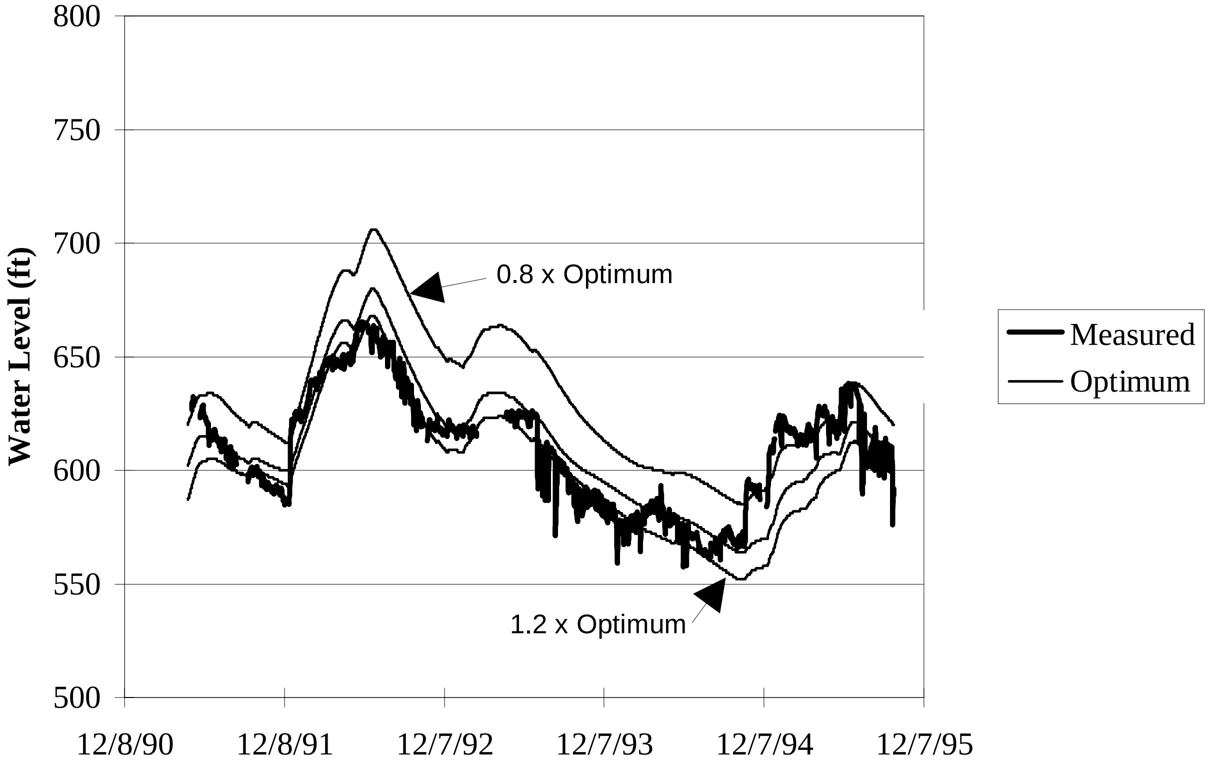

Figure 3.14 Sensitivity of Onion Cell Water Level to Hydraulic Conductivity

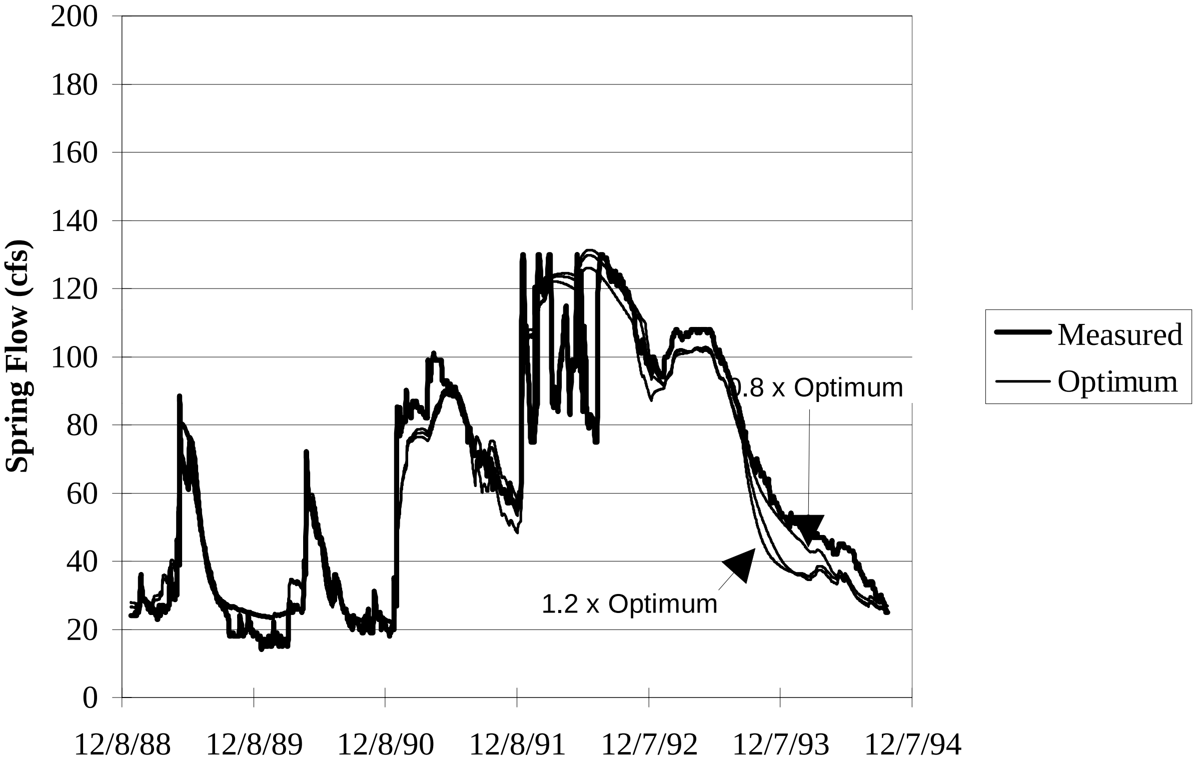

Figure 3.15 Sensitivity of Spring Flow to Hydraulic Conductivity

The effect of variation in the values of tank effective area was investigated with the same criteria used for evaluation of changes in hydraulic conductivity. As before, values 20% above and below the optimum values were used for the sensitivity study. The effect on predicted spring discharge for the recession curve shown for the period in 1979 is shown in Figure 3.16. Increasing the effective area causes the spring flow prediction to be higher than the measured rate, whereas decreasing the area reduces the predicted discharge. A comparison of measured with predicted water levels for the Onion cell is shown in Figure 3.17. Decreasing the effective area increases the range of predicted water levels, with the levels rising higher when recharge is occurring and then falling faster during recession periods. Increasing the area reduces the range of predicted levels and slows the fall during dry periods. A comparison of the variation in spring discharge is shown in Figure 3.18. As was the case with hydraulic conductivity, the overall difference in the predicted spring flow is fairly small. These simulations indicate the model is robust and performs fairly well even with considerable variation in parameter values.

3.5 Numerical Accuracy and Stability

Since the model calculates flow between cells explicitly using Euler's method, a comparison with a more sophisticated integration technique was done to verify the numerical accuracy of the solution. The fourth order Runge-Kutta method was chosen for this comparison. Water levels in the five cells as well as total flow from Barton Springs were calculated with both methods for the period of 8/1/79 through 1/8/80. This was a period of minimal recharge and uninterrupted decline in both spring flow and head. The programming software "Stella II" (High Performance Systems, Inc., 1994) was used to calculate values for both methods. Differences between the two methods were negligible. For example, the initial head in the Slaughter cell was 550 feet, and the final heads predicted were 490.53 and 490.57 feet for the Euler and Runge-Kutta methods respectively. The total predicted spring flow for the same period were also similar, 975.8 x 10^6 ft^3 and 974.7 x 10^6 ft^3 for the Euler and Runge-Kutta methods, respectively.

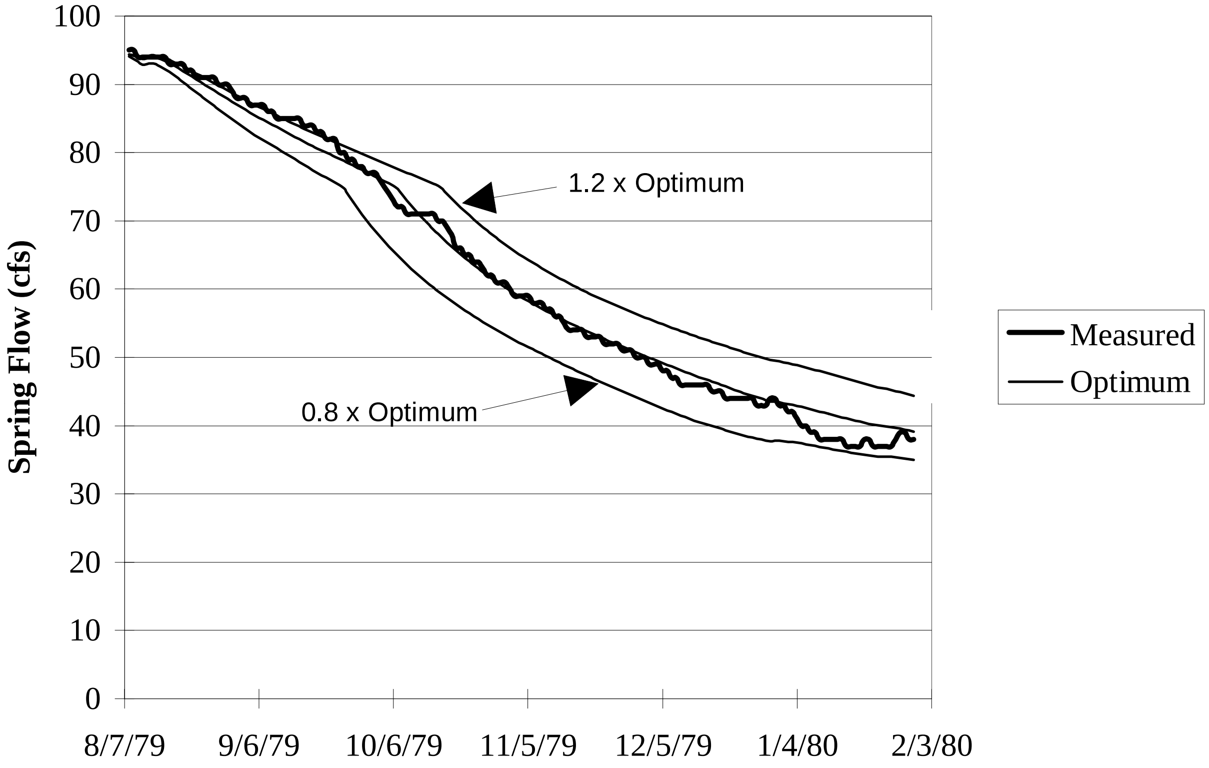

Figure 3.16 Sensitivity of Recession Curve to Effective Area

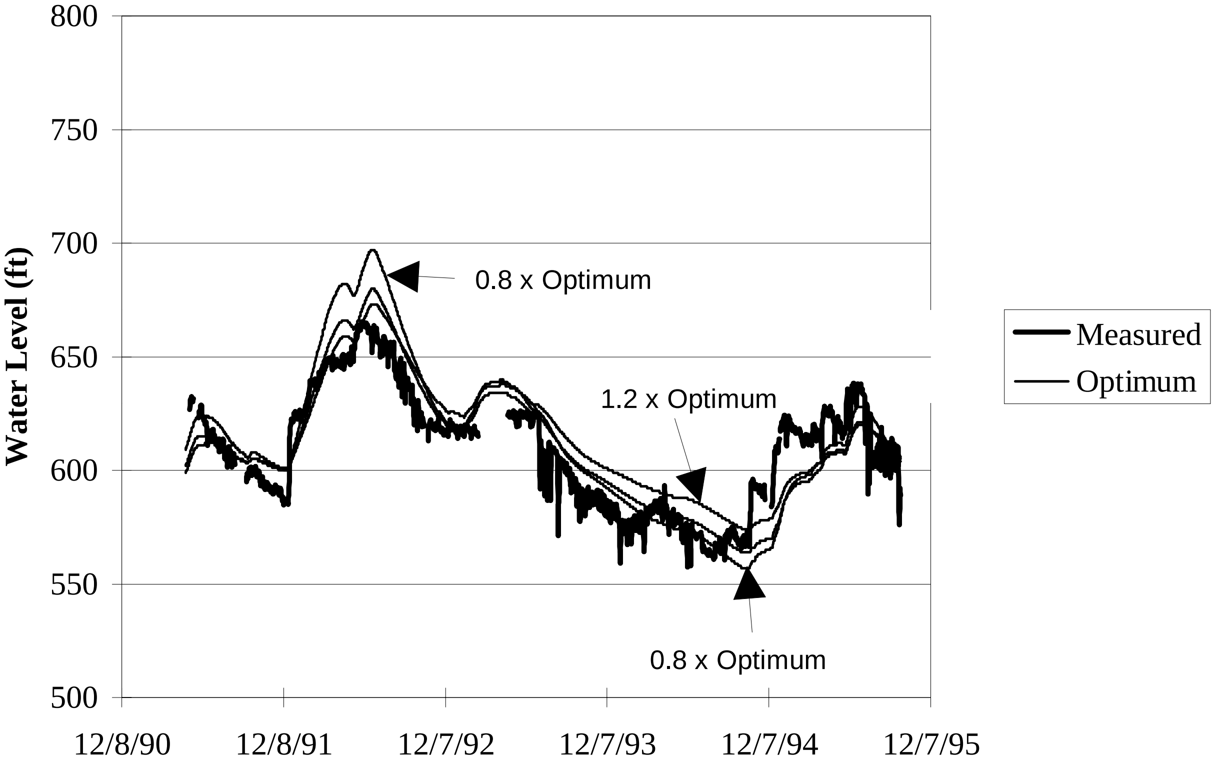

Figure 3.17 Sensitivity of Onion Cell Water Level to Effective Area

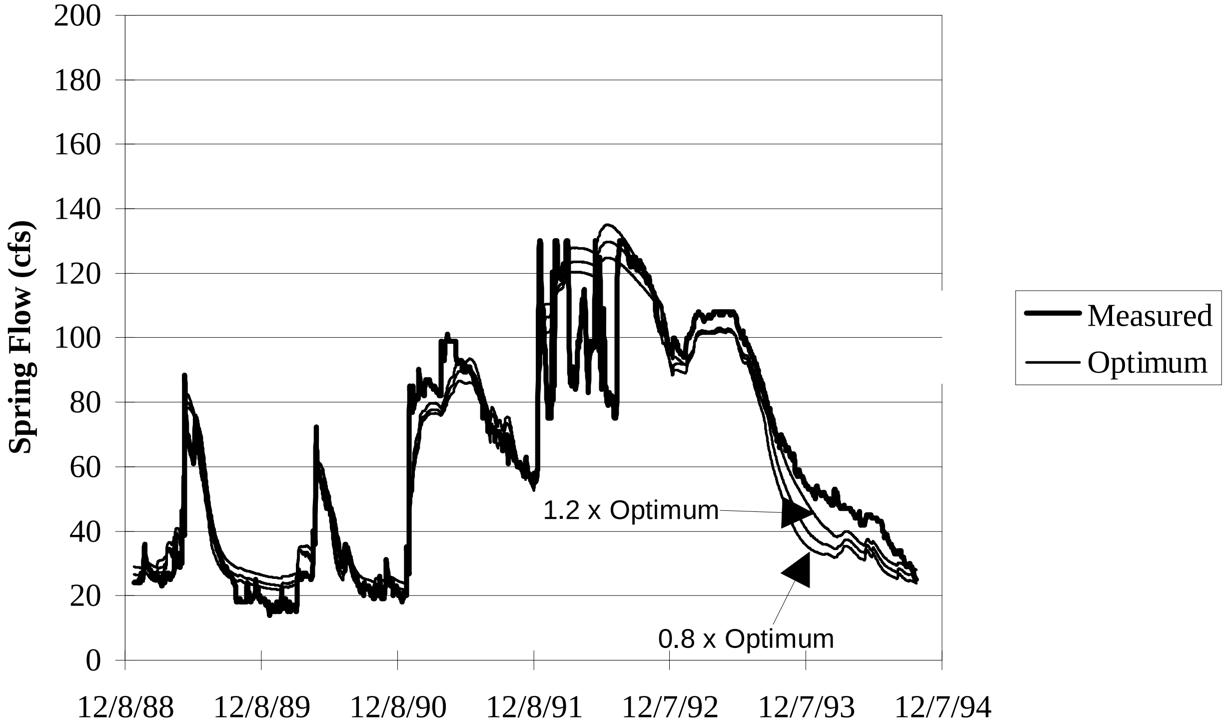

Figure 3.18 Sensitivity of Spring Flow to Effective Area

A water balance also was performed for the entire 16-year simulation period. The volume of water recharged to the aquifer from the creeks and diffuse infiltration totaled 3.83×10^{10} ft^3. Discharge from the aquifer from pumping, baseflow to Barton Creek, and spring flow totaled 3.88×10^{10} ft^3. Approximately 5×10^8 ft^3 was lost from aquifer storage based on beginning and ending water levels; consequently, the mass balance error for this period is less than 0.1%.

Rigorous criteria for judging numerical stability are commonly applied to groundwater models of confined aquifers. These criteria require that the differential equations being approximated are linear. The governing equations for this model are nonlinear; consequently, there are no formal criteria for absolute stability. A sense of the stability can be achieved by replacing the governing equation with a linear representation and substituting average values for the aquifer properties. In this case, the requirement for stability derived by Remson et al. (1971) states that:

$$\left(\frac{S}{T}\right)\frac{\Delta x^2}{\Delta t} \geq 2$$

where S is the storativity, T is the transmissivity, Δx is the distance between the centers of adjacent cells, and Δt is the length of the time step. Substituting typical model values for these parameters, the right-hand side of the equation becomes:

$$\left(\frac{0.6}{200000}\right)\frac{(12700)^2}{1} = 483$$

Therefore, the model would be stable under average conditions with time steps as large as one month. A 15-year simulation with the model executes in less than 10 seconds, so there is no real advantage to increasing the current time step.

3.6 Model Response to a Pulse Input

During periods of recharge, water entering the aquifer can create a localized mound or wave which propagates through the subsurface, causing abrupt increases in well water levels and spring discharge. To determine the response of the model to a large change in water level, the effect of a pulse input of water to the Onion cell was simulated. Prior to the input, the aquifer was simulated as a steady-state system with a constant rate of recharge of 50 cfs in the Onion cell. No recharge was occurring in the other cells. A instantaneous input of 4.35×10^8 ft^3 of water was added to the cell, resulting in a 50-foot increase in water level. The resulting water levels in the aquifer cells are shown in Figure 3.19.

The increase in water level propagates through the system very rapidly, with a noticeable increase in the water level of the Barton cell occurring after about 20 days. The rise is most abrupt in the cells closest to the input point in the Onion cell and gradually diminishes in the farther cells. The amount of rise in any particular cell is a function of the effective area of the cell and its proximity to the recharge point.

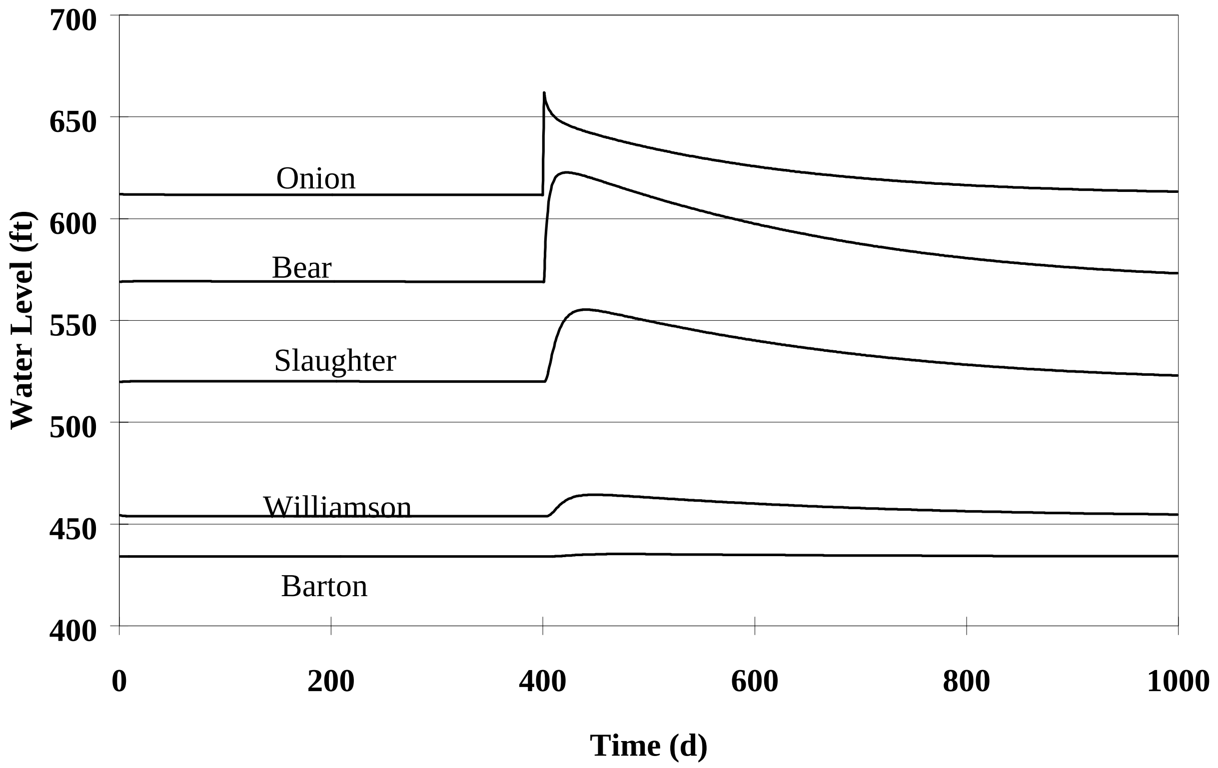

Figure 3.19 Model Response to a Pulse Input of Water

4. Water Quality Model

Constituent transport was incorporated into the model by treating each of the cells as a completely mixed tank. As such, any constituent input to the aquifer is assumed to be instantaneously mixed with the entire cell volume. The constituent is assumed to be conservative and soluble. No retardation was assumed because of the expected small organic carbon content of this limestone aquifer. A daily mass balance was computed based on the mass entering and leaving each cell during each time step. In this formulation, the model predicts an average concentration in the cell based on the mass of constituent and the volume of water in the cell. This concentration represents an average over a relatively large area and is most useful for estimating relative changes in concentration rather than an exact concentration at a particular time and place; therefore, the model is more appropriate for nonpoint sources of contamination.

4.1 Calculation of Input Mass to Aquifer

Mass enters the aquifer via creek recharge and diffuse recharge. The mass entering each cell from recharge to the creeks is calculated from the daily average flow rate in the creek and an average daily concentration. As explained in the preceding chapter, the model estimates daily recharge volume based on the flow rate in the creek upstream of the recharge zone. The following equation is used to calculate the mass of the constituent in the recharge from each of the five creeks:

$$M_c = 2.45 \times Q_R \times C_C \times 1 \text{ day}$$

where M_c is the mass of constituent in creek recharge (kg), Q_R is the average creek recharge rate (cfs), C_C is the concentration of the constituent in the creek water (mg/L), and 2.45 is a constant for units conversion.

The mass entering each cell from diffuse recharge was calculated based on the surface area of the cell over the recharge zone, the average daily rate of infiltration, and the average concentration in the diffuse recharge. The average rate of infiltration was assumed to be constant for the entire study area, although the user can vary the rate of infiltration by changing the effective surface area of the individual cells. The concentration of the diffuse recharge for each of the cells is assumed to be constant for the simulation and is specified in the simulation input file. The mass entering each cell daily is calculated with the following equation:

$$M_d = 28.32E-6 \times A \times q_i \times C_D \times 1 \text{ day}$$

where M_d is the mass of constituent in diffuse recharge (kg), A is the surface area of each cell over the recharge zone (ft^2), q_i is the average rate of diffuse infiltration (ft/d), C_D is the average concentration of constituent in diffuse infiltration (mg/L), and 28.32E-6 is a constant for units conversion.

4.2 Calculation of Mass Output from Aquifer

Mass leaves the aquifer via pumping wells, discharge to Barton Springs, and as baseflow to Barton Creek during periods of high water levels in the aquifer. The amount of mass leaving a cell through well pumping is calculated based on the average concentration in the cell and the volume of water pumped. The following equation expresses this relationship:

$$M_p = V_p \times \frac{M}{V_t}$$

where M_p is the mass leaving the tank via pumping (kg), V_p is the volume of water pumped from tank (ft^3), M is the mass of constituent in the tank (kg), and V_t is the volume of water in the tank (ft^3).

The mass of constituent discharged at Barton Springs is a function of the flow rate of the springs and the concentration in the Barton cell. In the model, this is calculated as:

$$M_s = 86{,}400 \times Q_S \times \frac{M_b}{V_b} \times 1 \text{ day}$$

where M_s is the mass discharged at Barton Springs (kg), Q_S is the predicted flow rate of Barton Springs (ft^3/s), M_b is the mass of the constituent in the Barton cell (kg), and V_b is the volume of water in the Barton cell (ft^3).

The mass discharged to the lower reaches of Barton Creek is calculated in the same manner as the mass discharge out of Barton Springs such that:

$$M_b = 86{,}400 \times Q_B \times \frac{M}{V_b} \times 1\ day$$

where M_b is the mass discharged as baseflow to Barton Creek (kg), Q_B is the rate of water discharge to the creek (ft^3/s), M is the mass of constituent in the Barton cell (kg), and V_b is the volume of water in the Barton cell (ft^3).

4.3 Calculation of Mass Transfer Between Cells

Mass is transported between cells via the processes of advection and dispersion. The amount of mass transferred by advection is a function of the flow rate, concentration of the upstream cell, and time step. This relationship can be expressed by:

$$M = Q \times C \times \Delta t$$

where M (kg) is the mass transferred during the time step, Q is the flow rate (ft^3/s), C is the concentration (kg/ft^3), and Δt is the length of the time step.

The amount of diffusion across a boundary is expressed by Fick's law, which states that:

$$J = D \times \frac{\partial C}{\partial x}$$

where J is the mass flux (kg/ft^2), D is the diffusion coefficient, and $\partial C / \partial x$ is the concentration gradient. Since the amount of diffusion is a function of the concentration gradient between cells as well as the velocity of the water, a spatial dimension is required in this expression. This distance was taken to be the straight line distance between the key wells in each cell. In general, diffusion is insignificant because of the low regional concentration gradients.

Laboratory experiments with porous media indicate that D is a function of the groundwater velocity such that:

$$D = a_L \times v$$

where a_L is the longitudinal dispersivity and v is the velocity in the direction of flow (Domenico and Schwartz, 1990). Substituting this relationship in the discrete form of Fick's law and multiplying both sides of the equation by the area between the cells gives:

$$M = a_L \times Q \times \frac{\Delta C}{L}$$

The equations for advection and dispersion are combined in the model as:

$$M_j = 86{,}400 \times Q_j \left((C) + a_L \left(\frac{\Delta C}{L} \right) \right) \times 1 \text{ day}$$

where M_j is the mass transferred across j^{th} boundary (kg), Q_j is the flow across the boundary (ft^3/s), C is the concentration in the upstream cell, a_L is the dispersivity (ft), ΔC is the difference in concentration between adjacent cells, and L is the distance between key wells (ft).

4.4 Calculation of Cell Mass Balance

The mass balance for each cell is calculated daily based on the amount in the cell at the end of the preceding time step and the amount entering and leaving the cell during the current time step. The mass in all the cells except Barton is calculated by the following formula:

$$M\big|_{t+\Delta t} = M\big|_{t} + (M_d + M_c - M_p + \sum M_j)\big|_{t+\Delta t}$$

Since the Barton cell also loses constituent mass through discharge at Barton Springs and as baseflow to Barton Creek, a slightly more complex formula is required to calculate the mass balance in that cell:

$$M\big|_{t+\Delta t} = M\big|_{t} + (M_d + M_c + M_j - M_b - M_s - M_p)\big|_{t+\Delta t}$$

4.5 Transport Model Inputs

Simulation of transport in the aquifer requires the identification of a suitable constituent which exhibits variation in concentration, is conservative, and whose sources can be quantified. Analysis of water quality data from Barton Springs indicated that nitrogen (as nitrate in the aquifer) might be such a constituent. This was the only conservative constituent which exhibited any long-term variation in concentration at Barton Springs. In addition, the increasing use of septic tanks has led to concerns about potential increases in nitrogen concentration in the aquifer. Nitrogen is a key element in the life processes of plants and animals and is one of the basic building blocks of life. However, too much nitrogen can cause severe degradation of the environment and has been linked to health problems such as methemoglobinemia and cancer.

4.5.1 Nitrogen Sources

Nitrogen inputs to the aquifer may consist of recharge from creeks, septic tank effluent, rainfall infiltration, runoff/leaching from fertilized lands, and leaking sewer pipes.

Creek Recharge

USGS and Texas Natural Resource Conservation Commission (TNRCC) water quality data were analyzed for the creeks crossing the recharge zone. A mean total nitrogen concentration was found for each creek, and a final weighted total nitrogen concentration was computed for the recharge from the creeks based on these means.

Water quality data have been collected by the USGS and TNRCC at several gauging stations set up along the six creeks that cross the recharge zone. Figure 4.1 shows the locations of the gauging stations used in this study. The data sets varied in size from creek to creek, and one data set had only 10 measurements over a 10-15 year time period (Little Bear). The water quality data were separated by gauging station, with samples collected during storm flow and baseflow treated separately. The basis for the separation was determined by analyzing the creek flow rate and suspended solids concentrations. An increase in flow rate and suspended solids over a short period of time (hours) indicated that the measurements taken during that time period were associated with stormflow.

During storms, multiple samples were usually collected. The individual samples were not representative of the average storm flow conditions because the sample concentrations varied greatly depending on when the sample was taken during the storm. In order to obtain a more meaningful value, the readings taken during the storm were replaced with a single, flow-averaged value.

A mean for the baseflow and the storm flow data was calculated for each nitrogen species at each gauging site. After the means for each gauging station were computed, a mean for each watershed was found by averaging the means at each station in the watershed. The concentrations of the individual species were summed to determine the total nitrogen concentration in surface water for that watershed.

The mean baseflow total nitrogen concentration for each of the creeks is shown in Table 4.1. The concentrations ranged from a high of 1.26 mg/L to a low of 0.50 mg/L. It should be noted, however, that the 1.26 mg/L was measured at Little Bear and that there were only three measurements for each of the three nitrogen species examined at Little Bear. The effect of having only three baseflow data points for Little Bear is offset by the small contribution of the watershed to aquifer recharge.

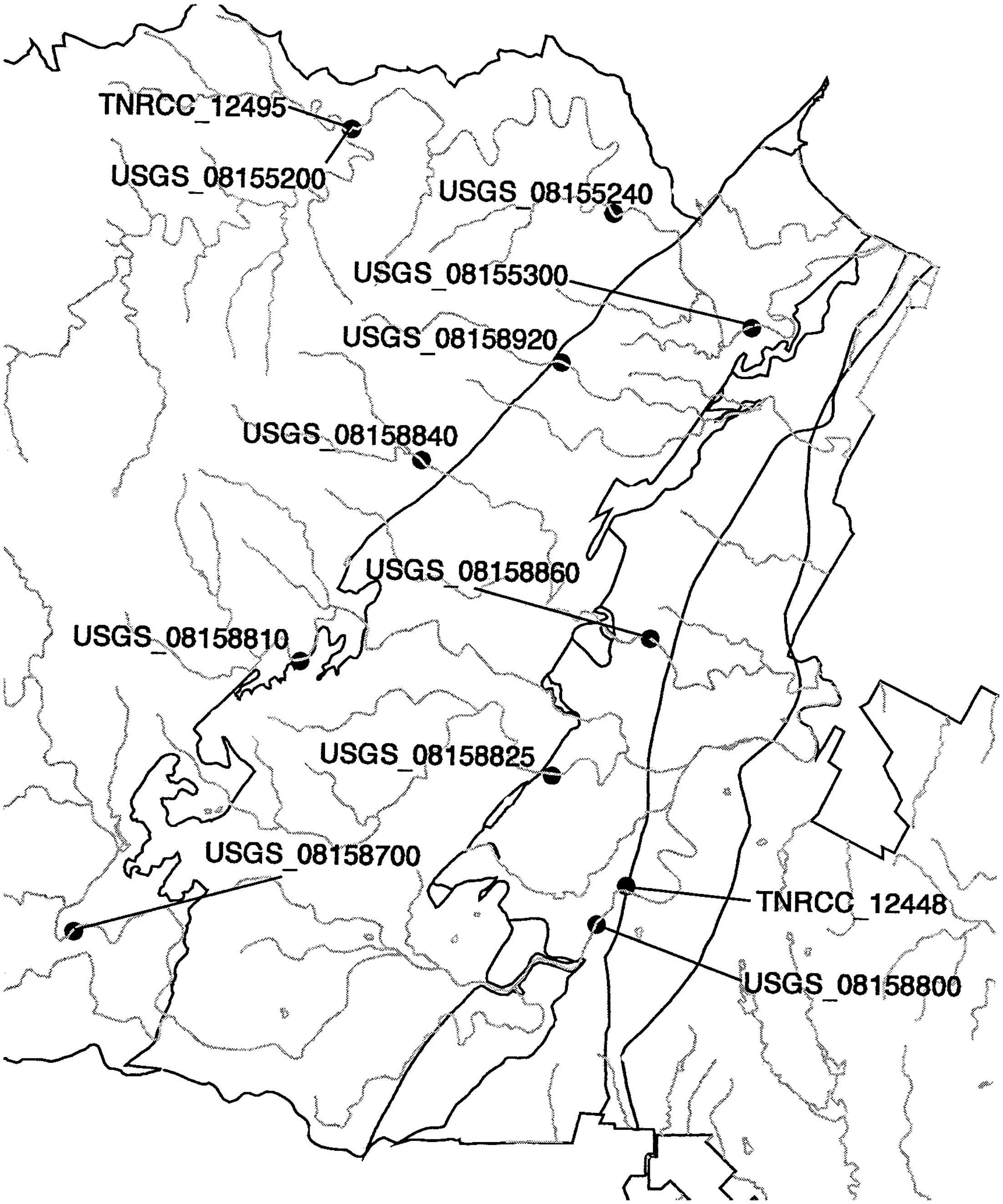

Figure 4.1 Location of Surface Water Monitoring Sites

Table 4.1 Average Nitrogen Concentrations for the Creeks During Baseflow

Creek	Nitrate (mg/L)	Total Kjeldahl (mg/L)	Nitrite (mg/L)	Total Nitrogen (mg/L)
Barton	0.16	0.33	0.01	0.50
Williamson	0.46	0.41	0.01	0.88
Slaughter	0.22	0.35	0.02	0.59
Bear	0.26	0.34	0.01	0.61
Little Bear	0.58	0.67	0.01	1.26
Onion	0.23	0.29	0.03	0.55

The second highest mean baseflow total nitrogen concentration, 0.88 mg/L, was measured at Williamson Creek. However, even though its mean total nitrogen concentration is the second highest, Williamson Creek only supplies 3% of the recharge water, making the nitrogen contribution from Williamson small compared to the other creeks. The two lowest baseflow concentrations (0.50 mg/L and 0.55 mg/L) were measured at Barton and Onion Creeks, which is significant since they are the two largest sources of creek recharge (31% and 46%) to the aquifer.

Mean storm flow total nitrogen concentrations are shown in Table 4.2. The storm flow concentrations were consistently higher than mean baseflow concentrations and ranged from a high of 2.79 mg/L to a low of 0.68 mg/L. The highest value was recorded at Williamson Creek. Little Bear had the second highest mean total nitrogen concentration (1.66 mg/L) for storm flow; however, this value is based on only 7 measurements for each of the 3 nitrogen species over a 2-year time period. Onion has the lowest mean total nitrogen concentration of 0.68 mg/L for storm flow and contributes the largest amount of recharge to the aquifer.

Table 4.2 Average Nitrogen Concentrations During Direct Runoff

Creek	Nitrate (mg/L)	Total Kjeldahl (mg/L)	Nitrite (mg/L)	Total Nitrogen (mg/L)
Barton	0.23	1.04	0.02	1.29
Williamson	0.35	2.40	0.04	2.79
Slaughter	0.26	1.11	0.02	1.39
Bear	0.22	0.68	0.02	0.92
Little Bear	0.36	1.27	0.03	1.66
Onion	0.28	0.37	0.03	0.68

Septic Tanks

Another potential source of nitrogen into the Edwards aquifer is septic tanks, which contribute nitrogen to the aquifer in the form of organic, ammonia and nitrate nitrogen. The septic system effluent which is discharged to the drainfield may have a total nitrogen concentration of up to 70 mg/L.

The Barton Springs Edwards Aquifer Conservation District used 1990 U.S. census data to estimate that there are approximately 5900 septic tanks over the recharge zone (S. Bowlin, personal communication). Approximately 2050 are located on the Hays County portion of the recharge zone, whereas the remaining 3,850 are in Travis County.

The nitrogen load supplied to the aquifer by septic systems is difficult to determine through monitoring because of the uncertainty in the amount of water which infiltrates. The average concentration of total nitrogen leached to the aquifer from septic systems can be estimated from two monitoring studies conducted in the Travis County area. Parten and Liljestrand (1995) monitored two systems using a conventional design and found average concentrations of 9.4 and 5.2 mg/L. The monitoring wells/lysimeters only produced enough moisture to sample following periods of significant rainfall, indicating that leaching from the drainfields occurs sporadically. Espey, Huston and Associates (1985) installed and monitored wells located in and near six septic system drainfields. The concentration of total nitrogen was measured in four of the deeper wells located adjacent to the drainfields and ranged from 4.5 to 33.3 mg/L. Based on the results of these two local monitoring programs, the average concentration of total nitrogen in the water leached to the aquifer is approximately 13 mg/L.

The computer model, Groundwater Loading Effects of Agricultural Management Systems (GLEAMS, v. 2.10) was used by Kam (1996) to estimate the input of nitrogen to the Barton Springs portion of the Edwards aquifer from septic systems. GLEAMS is a mathematical model that can assess the effects of climate-soil-management interactions in an agricultural system. GLEAMS will perform a water balance and nutrient balance (phosphorus and nitrogen) and can also model the movement of pesticides through the subsurface (Knisel, 1993).

The GLEAMS input parameters were based on a drainfield area of 1600 ft^2 and Type C or clay loam soils. Bermuda grass with an effective rooting depth of 36 inches was assumed to cover the field. The nutrient input file contains information about the amount of nutrients and organic matter in the soil horizons and the quantity and composition of fertilizer. The model is fairly sensitive to the amount of nitrogen that is contained in the effluent supplied to the drainfield. For this simulation, an average concentration of 40 mg/L was used, which is the concentration reported by the EPA (1980).

An erosion input file for GLEAMS contains the parameters necessary for predicting the amount of surface erosion resulting from rainfall. Rainfall data from the National Weather Service Office in Austin, Texas, for the period 1973-1993 were used to create the rainfall input file. The simulation with the described parameter values predicted that an average concentration of approximately 12 mg/L of nitrate as nitrogen would be leached to the aquifer, which is very similar to measured values. The average percolation from the drainfield was 34 in/yr during the 20-year simulated period. The nitrogen load supplied to the groundwater would be about 1.5 kg/tank/yr and the volume of water would be 1.3×10^5 L/tank/yr. Based on these two studies, the volume of water leached to the aquifer was assumed to be 1.3×10^5 L/tank/yr with an average nitrogen concentration of 13 mg/L.

Diffuse Recharge

Diffuse recharge consists of precipitation that infiltrates directly into the aquifer. The nitrogen load derived from diffuse recharge was estimated using GLEAMS. The nitrogen load leached to the aquifer is a function of climate, vegetation, and soil properties. Kam (1996) analyzed the USGS land use/land coverage data and identified the four vegetative covers which are listed in Table 4.3.

Table 4.3 Summary of Vegetative Cover

Description of Vegetation	Percent of Recharge Zone
Shrub/Brush	0.8%
Cropland/Pasture	3.9%
Deciduous Forest	61.4%
Mixed Rangeland	33.9%

Deciduous forest and mixed rangeland are the two dominant vegetative covers over the recharge zone. Shrub/brush and cropland/pasture were ignored because of their relatively small size, and their corresponding land areas were lumped with the mixed rangeland. Therefore, it was estimated that the recharge area is approximately 60% deciduous forest and 40% mixed rangeland.

The original plan was to estimate infiltration and nitrogen leaching from these two sources using GLEAMS; unfortunately, there is an error in the nutrient calculations of the current version (v. 2.1) which results in no plant uptake of nitrogen for forests. The presence of this flaw was confirmed by Mr. Kevin King (personal communication) at the U.S. Department of Agriculture. However, the model can be used successfully to estimate the infiltration from both land covers and the concentration and load from rangeland. The concentration of nitrogen in groundwater below these two land uses is similar (Juergens-Geschwind, 1989), so the concentration predicted for rangeland can be used with the infiltration predicted for forests to generate an approximation of the nitrogen load from forests.

The input parameters for the GLEAMS hydrology file describe a silty clay loam soil (Type C) with a slope of 2% and an SCS curve number of 79. The only relevant information in the nutrient file is the concentration of nitrate in the rainfall (1.5 mg/L). The difference between rangeland and forest land input files is the value for vegetation type. All vegetation is assumed to have an effective rooting depth of 36 inches.

To ensure that the initial values chosen would have little impact on the predicted results, a 15-year simulation was performed. The rainfall input file consisted of historical data from the Austin Weather Service collected between 1979 and 1993. During this period, the average yearly rainfall was 33.4 inches, close to the long-term historical average of 32.5 inches. Based on the above input data, GLEAMS predicts that the average rate of infiltration to the aquifer for rangeland is 2.9 in/yr with a nitrogen load (all NO_3) of about 3.9 kg/ha/yr. The resulting NO_3 concentration of this water would be 5.3 mg/L. For forest land, GLEAMS predicts an average rate of infiltration of 1.38 in/yr If the concentration of this water is similar to that derived from rangelands, then the load to the aquifer would be 1.8 kg/ha/yr. This value is very similar to the nitrate load from forests of 1.5 kg/ha reported by Gold et al. (1990). Based on the relative area covered by each of these vegetation types, the average rate of diffuse infiltration to the aquifer would be 2.0 in/yr with an average concentration of 5.3 mg/L. The total average annual load of nitrogen to the aquifer in diffuse recharge would be about 54,000 kg/yr and the rainfall infiltration volume would be approximately 3.7×10^8 ft^3.

4.5.2 Input Values

Transport of nitrogen in the aquifer was simulated for the period 8/79-10/95. The creek concentration on specific days during that period was estimated by assuming that days with an average flow rate at least 50% higher than the previous day were dominated by storm flow. All other days are assumed to have the water quality typical of baseflow conditions. Since the groundwater model treats Bear and Little Bear Creeks together, the concentrations from the two watersheds were averaged together to develop a single concentration for the creek recharge to the Bear cell.

Diffuse recharge was assumed to occur at a constant rate. The concentration of a constituent in diffuse recharge was considered to be constant for individual cells. The model allows input of different concentrations for each cell so the number of septic systems in each cell was estimated and a weighted average concentration of total nitrogen was calculated for each cell. The effective concentration was determined by taking the weighted average of the concentrations in rainfall and septic tank infiltration. Table 4.4 shows the assumed distribution of septic systems and the average nitrogen concentration assigned to deffuse infiltration. The average annual mass input of nitrogen for all sources is shown in Table 4.5. The effects of dispersion were neglected for these simulations.

Table 4.4 Estimate of Nitrogen Concentration in Diffuse Recharge

Cell	Number of Septic Systems	Average N Concentration
Onion	1000	5.55
Bear	2300	5.85
Slaughter	1300	6.81
Williamson	1300	6.60
Barton	0	5.30

Table 4.5 Summary of Average Annual Nitrogen Inputs

Source	Recharge (ft^3)	Average Conc. (mg/L)	Nitrogen Mass (kg)	% Total Known Mass
Creek Recharge	2.1×10^9	0.69	41,000	39
Septic Systems	2.7×10^7	13	10,000	9
Diffuse Recharge	3.7×10^8	5.3	55,000	52
Total =	**2.5×10^9**	**1.6**	**106,000**	**100**

4.6 Simulation Results

The model predictions for nitrogen concentration were compared to those measured at Barton Springs and in each cell. A comparison of model predictions with measured values at Barton Springs for the period of 1/89-10/95 is shown in Figure 4.2. The average concentration predicted by the model for this period was 1.46 mg/L; the average concentration of the measured values during this period was 1.48 mg/L. This agreement indicates that all the major sources of nitrogen have been identified.

The measured values show a greater variability, which is likely the result of two factors. Laboratory and sampling errors may result in reported values which differ from the actual values by 10% at this concentration level. In addition, recharge occurring in Barton Creek near the springs can result in rapid changes in discharge quality, which are not representative of average conditions in that portion of the aquifer.

The model predicts lower concentrations during periods of higher discharge. This is a result of the lower concentration of nitrogen in creek recharge diluting the aquifer concentrations. Figure 4.3 and Figure 4.4 show the relationship between discharge and concentration for predicted and measured values, respectively. The predicted concentrations in the five cells for the same time period are shown in Figure 4.5. The concentrations are lowest in the Onion and Barton cells and higher in the three intervening cells. This is a result of the lower concentrations of nitrogen in recharge water from Onion and Barton Creeks. The concentrations in the three middle cells also show more variation in quality. These cells are smaller than Onion and Barton and therefore the nitrogen concentrations change more rapidly in response to changes in the primary source of recharge. Diffuse recharge during dry periods (high nitrogen concentration) increases the concentrations in the cells and creek recharge during wet periods (low nitrogen concentration) tends to lower the concentration.

A geographical information system (GIS) database for the Barton Springs portion of the Edwards Aquifer was developed to allow a comparison of predicted and measured nitrogen data. All known sources of water quality data were combined into one large database, allowing spatial and temporal analysis of the data. The nitrogen distribution in the aquifer was analyzed for individual years and three extended time periods: pre-1980,

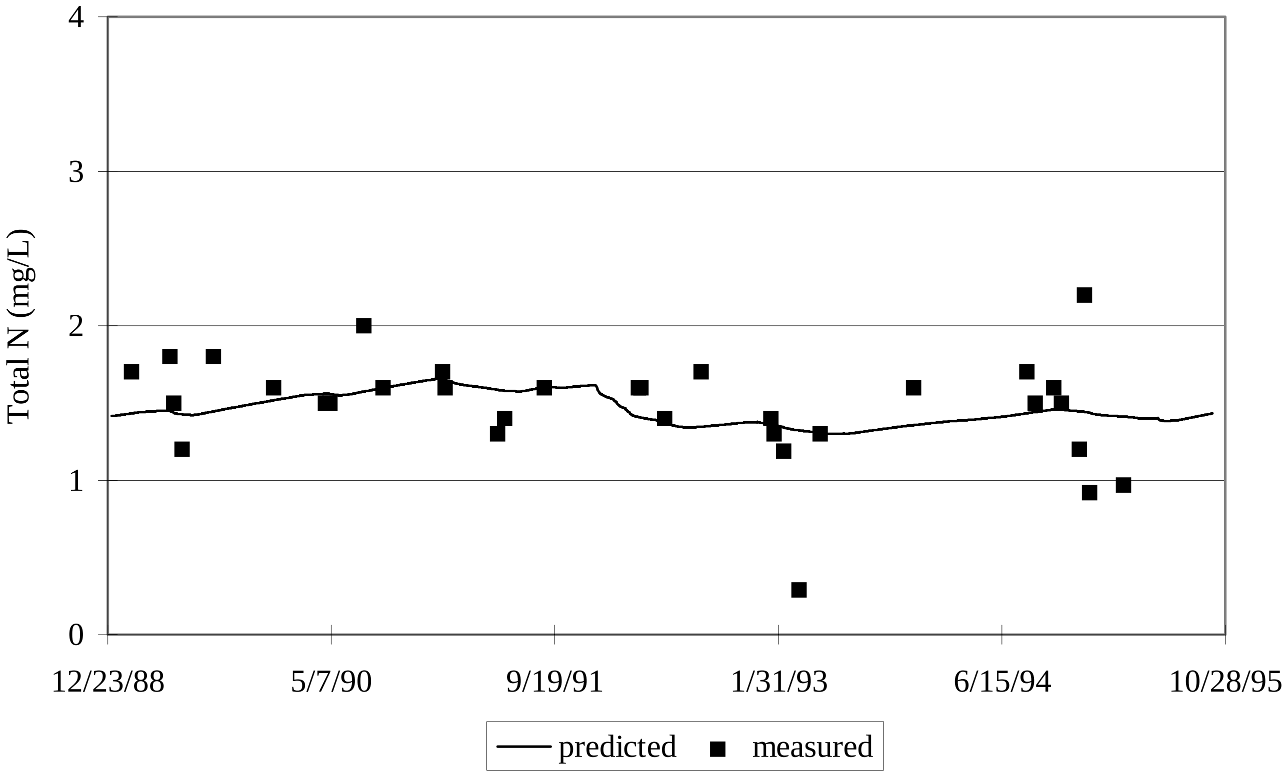

Figure 4.2 Comparison of Nitrogen Concentrations at Barton Springs

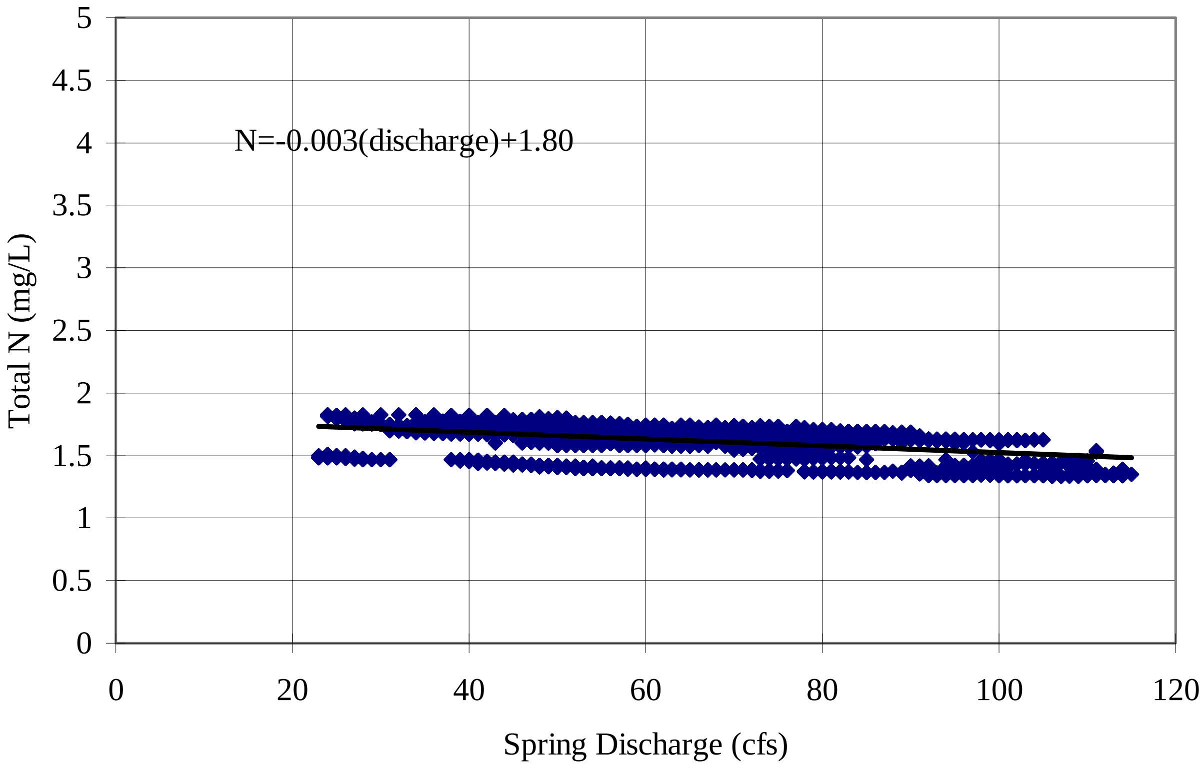

Figure 4.3 Predicted Relationship Between Discharge and Total Nitrogen

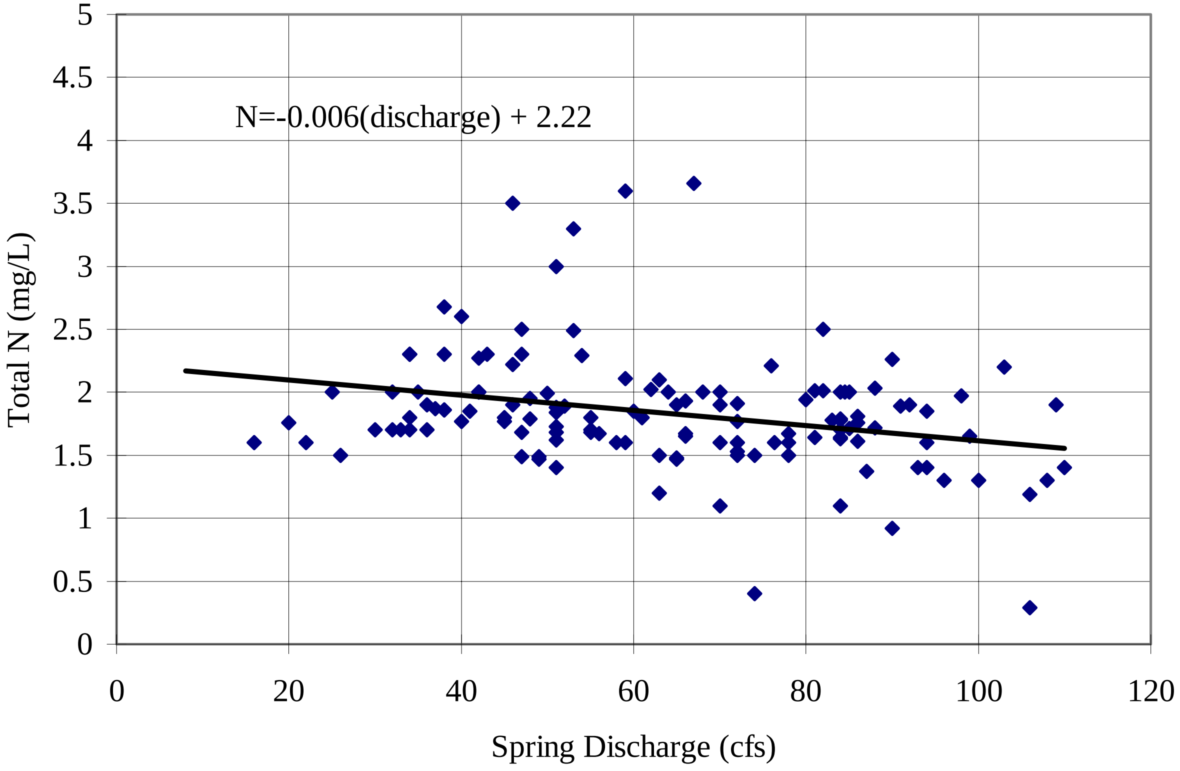

Figure 4.4 Measured Relationship Between Discharge and Total Nitrogen

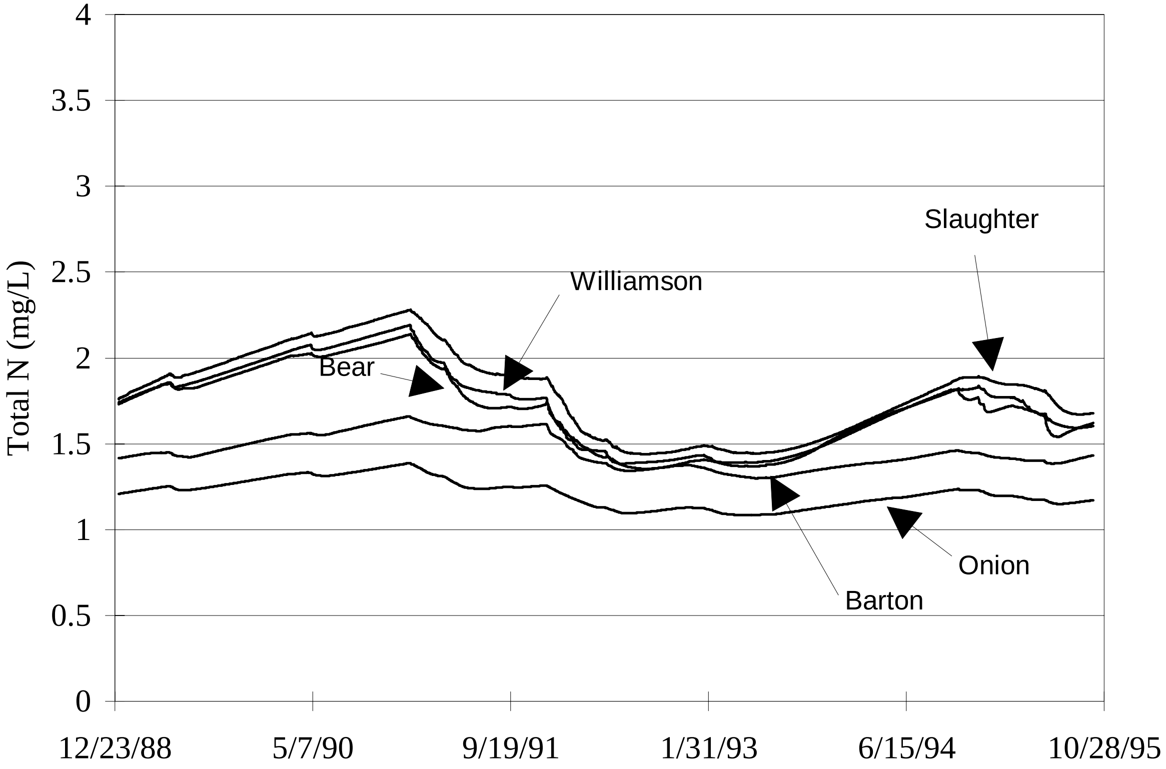

Figure 4.5 Predicted Nitrogen Concentrations in the Five Cells

1980-1990, and 1990-1995. These longer periods were selected to identify long-term changes in the nitrogen concentrations in the aquifer. The selection of specific time periods for analysis was not crucial since the nitrogen concentrations within the aquifer were fairly constant over the period of record.

Figure 4.6 shows the total nitrogen contours that resulted from the 1980-1990 data. Nitrogen concentrations are lowest in the northern and southern portions of the aquifer and highest in the central portion. Concentrations at both ends are generally between 1.0 - 2.0 mg/L, whereas concentrations in the central portions are between 2.0 and 5.0 mg/L. Higher concentrations in the center are the result of higher concentrations in the creeks supplying recharge in these areas. In addition, the well that consistently had the highest concentrations was located near animal pens.(Johns, personal communication, 1995). The distribution and concentrations of total nitrogen were similar for the other time periods analyzed. The data demonstrate that the distribution of the total nitrogen concentration within the aquifer has remained fairly constant over the last 20 years and that there is little variation in concentration between wet and dry years. Although the model predicts changes in concentration in response to recharge, for most years the concentration remains between 1.5 and 2.0 mg/L, which is not a large enough range to be easily documented in a field sampling program.

Histograms of the nitrogen concentrations in wells in each of the cells (Figures 4.7 through 4.11) support the conclusion that overall concentrations are higher in the Bear, Slaughter, and Williamson cells. The bimodal distribution of concentrations in the Slaughter cell is of particular interest. This distribution suggests the presence of a localized source of nitrogen input to the aquifer. The location of this source is clearly shown by the area of high concentration in Figure 4.6.

A mass balance for total nitrogen for the period 8/79-9/95 was calculated to verify the numerical accuracy of the model. The total mass input to the aquifer from diffuse and creek recharge totaled 1.67 x 10^6 kg, whereas the mass output was 1.72 x 10^6 kg. The mass lost from aquifer storage was 54,500 kg, the result of lower volumes and concentrations at the end of the simulation. The mass balance error for the 16-year simulation based on these numbers was less than 0.2%.

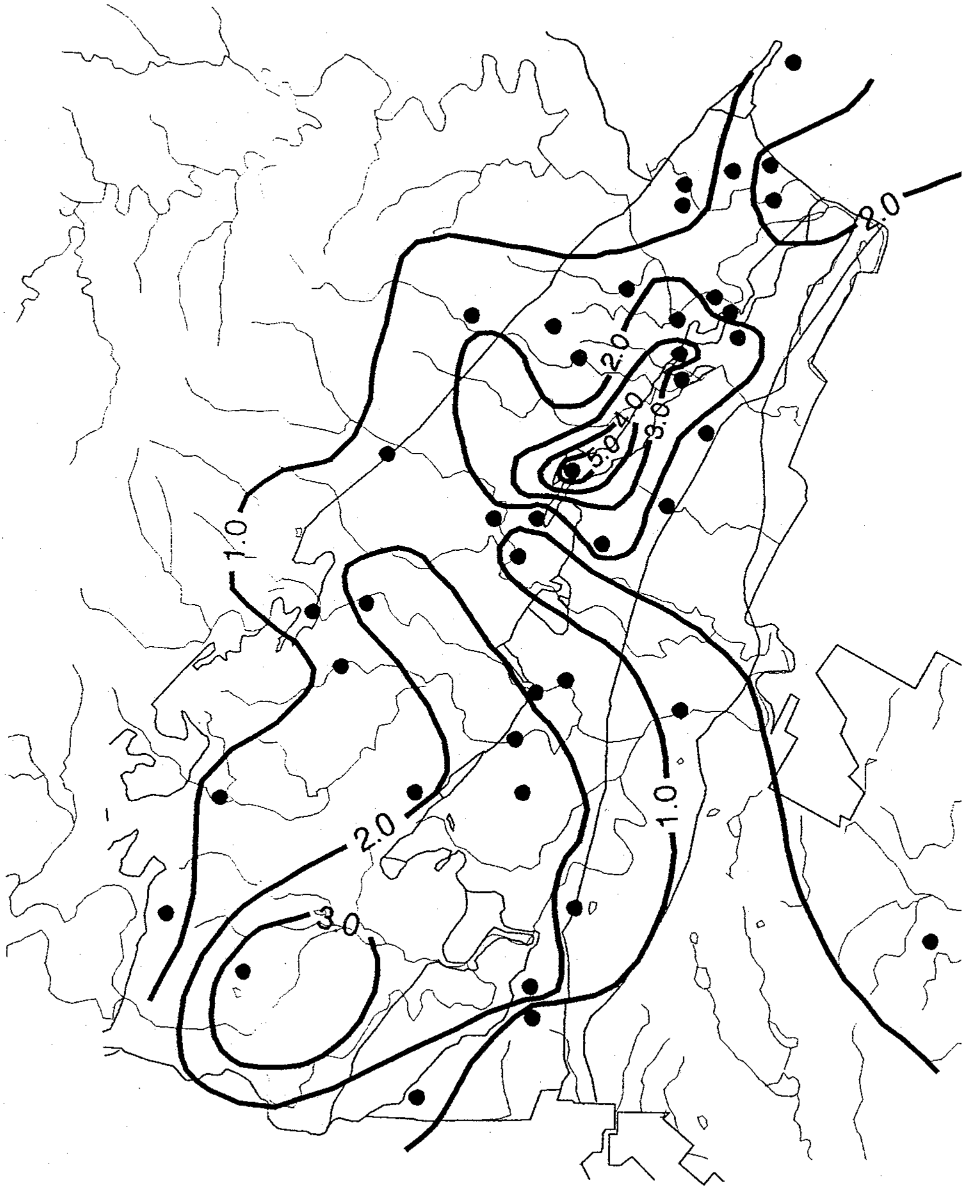

Figure 4.6 1980-1990 Total Nitrogen Contours

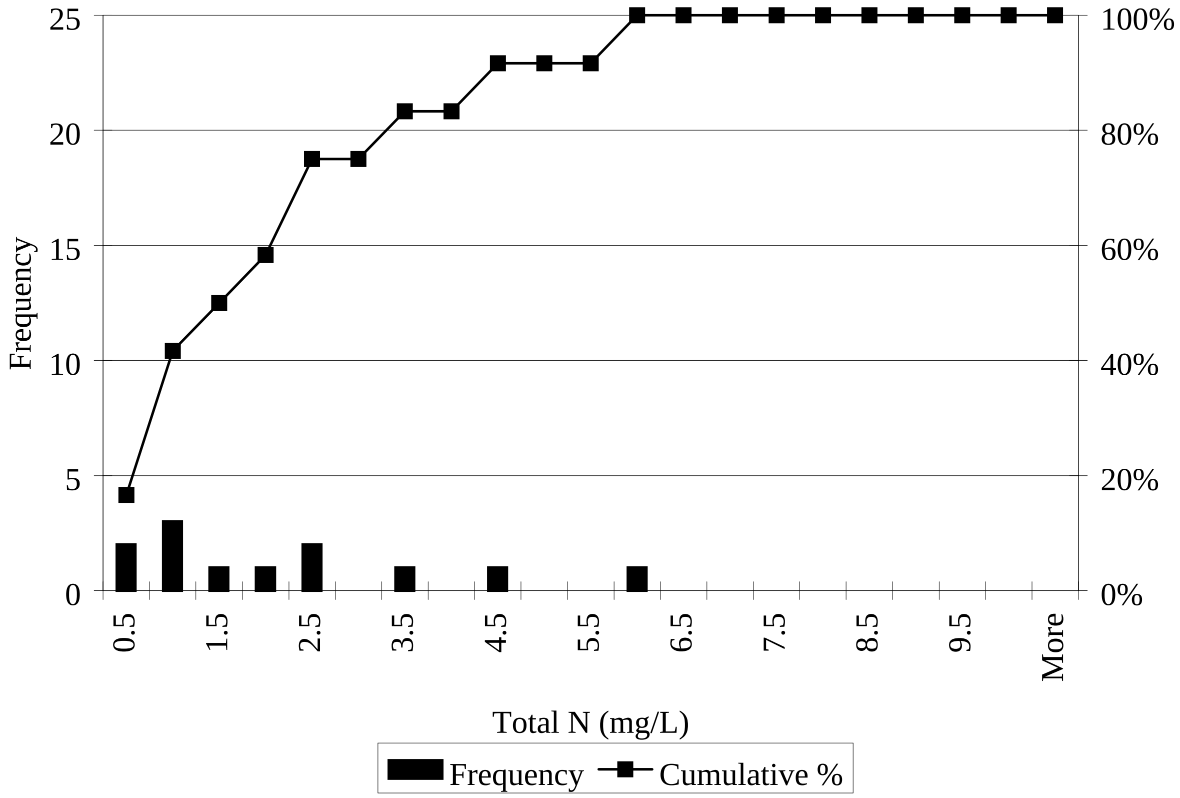

Figure 4.7 Histogram of Nitrogen Measurements in the Onion Cell

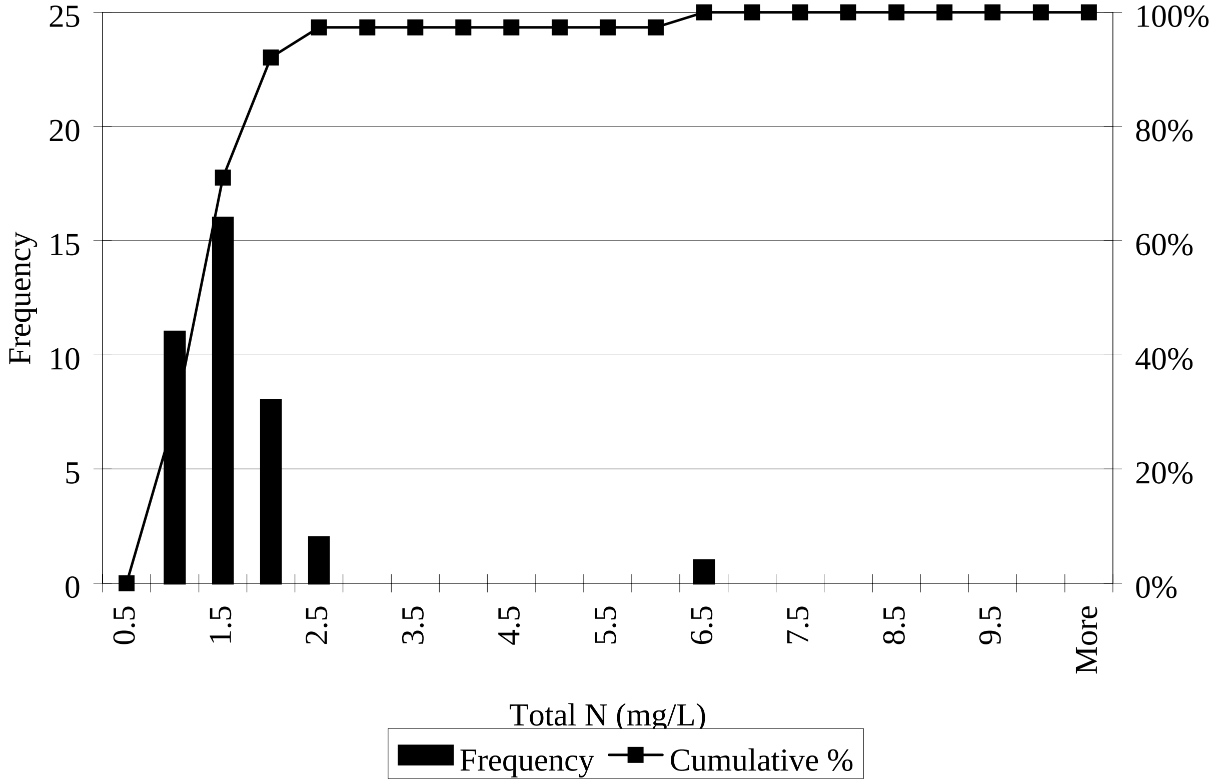

Figure 4.8 Histogram of Nitrogen Measurements in the Bear Cell

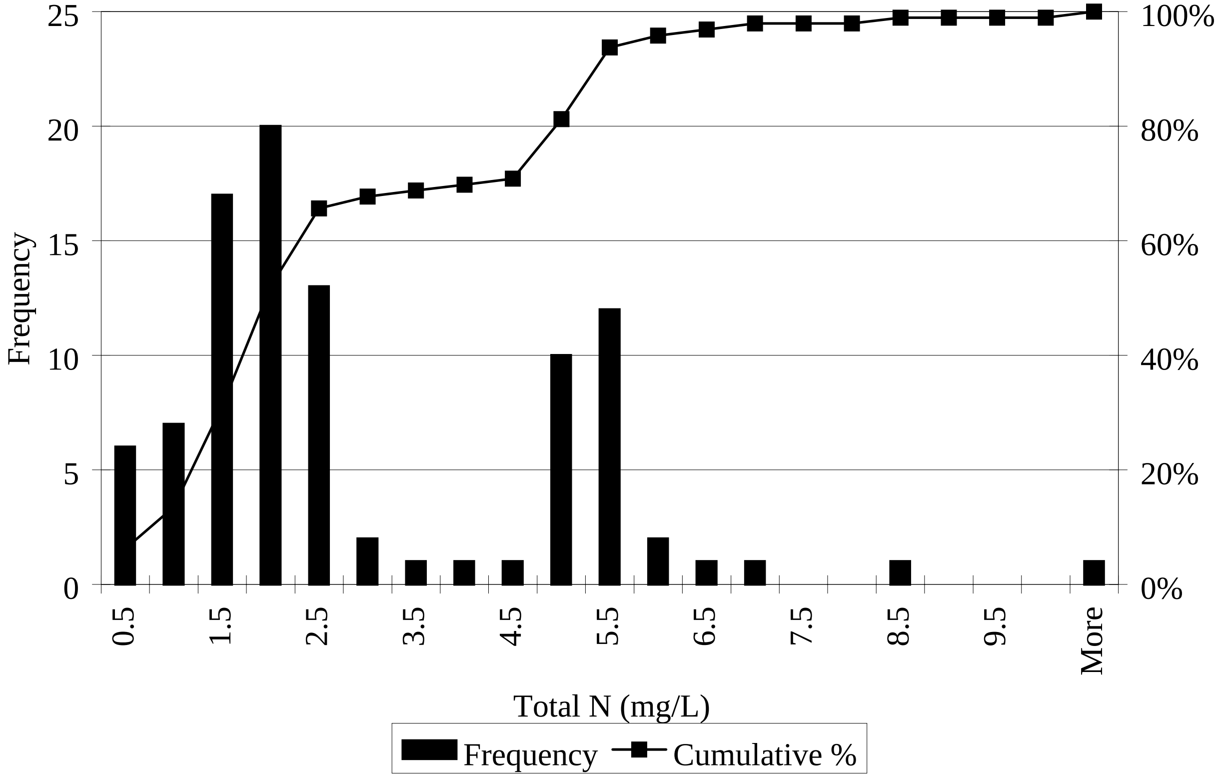

Figure 4.9 Histogram of Nitrogen Measurements in the Slaughter Cell

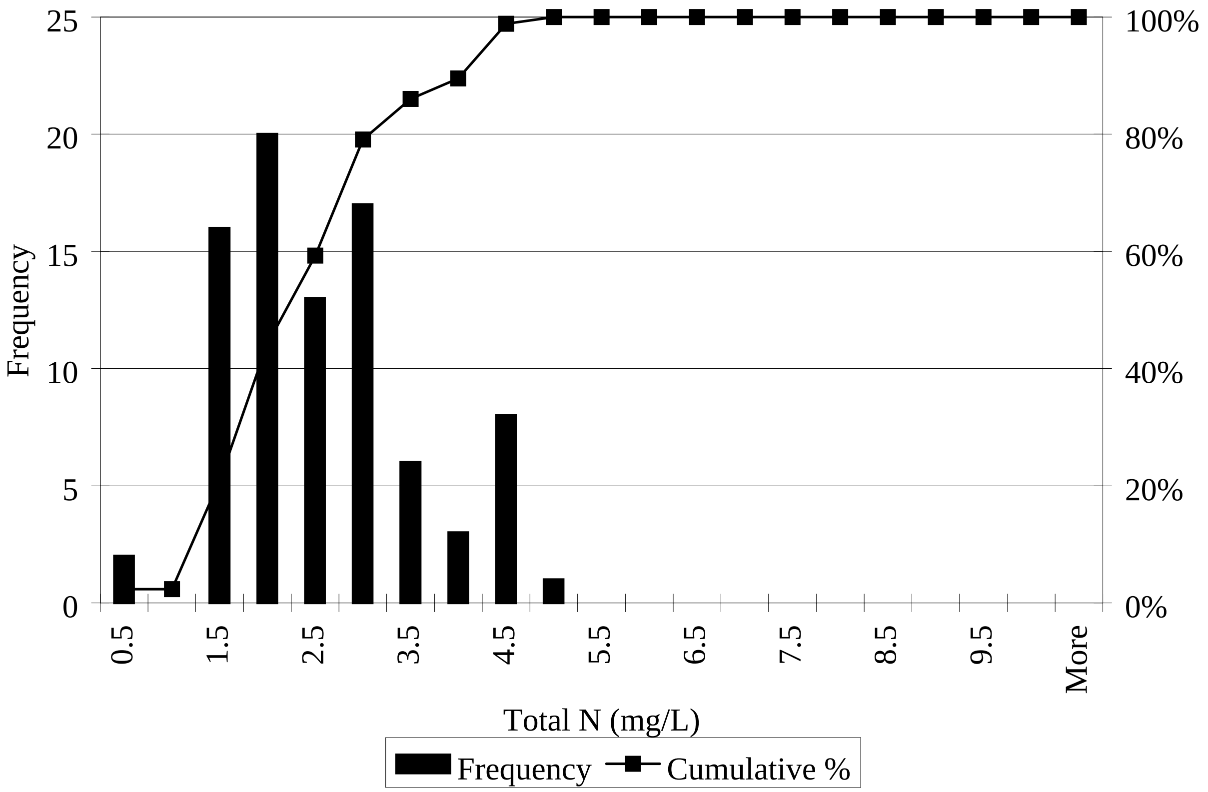

Figure 4.10 Histogram of Nitrogen Measurements in the Williamson Cell

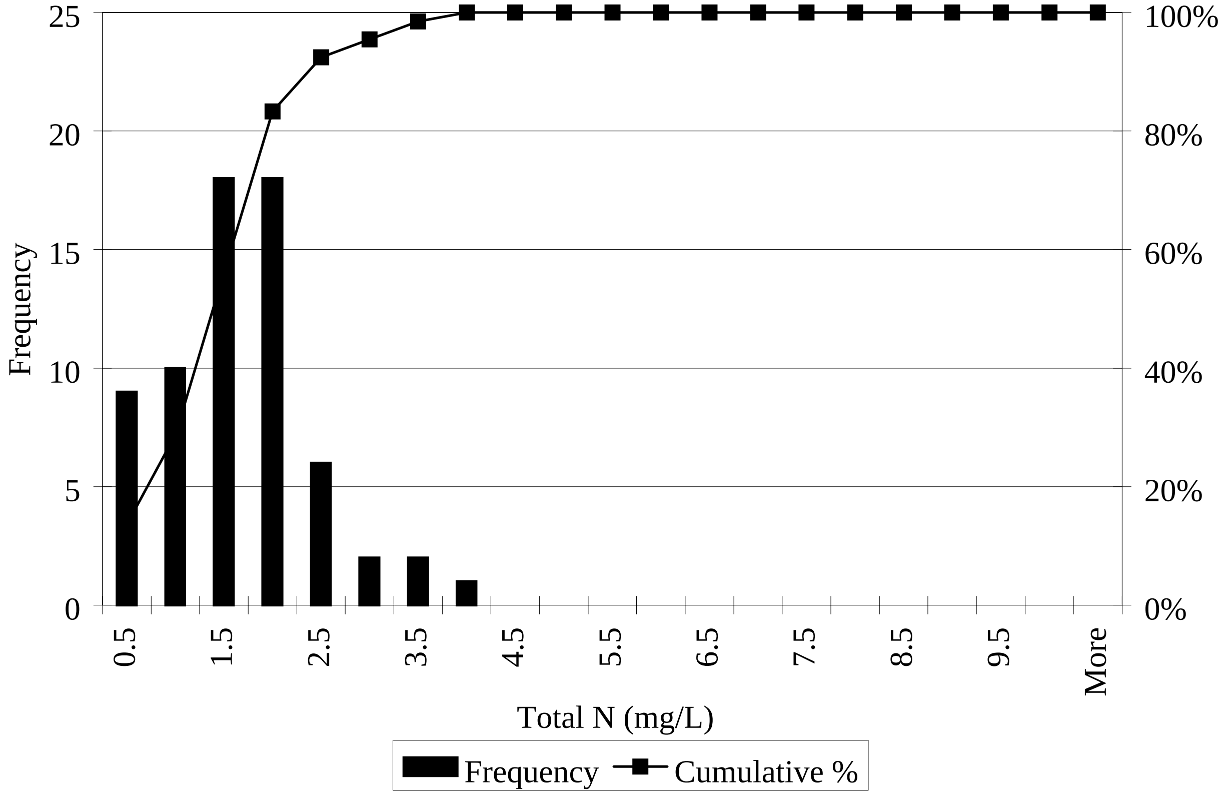

Figure 4.11 Histogram of Nitrogen Measurements in the Barton Cell

In summary, the dominant source of nitrogen to the aquifer is diffuse recharge, accounting for approximately 52% of the total nitrogen load. Creek recharge accounts for 39% and septic systems the remaining 9%. The average concentration of all known sources of recharge to the aquifer is approximately 1.46 mg/L. Nitrogen outputs are accounted for by discharge at Barton (88%), the lower reaches of Barton Creek (6%), and well pumpage (6%). Barton Springs flow is the primary discharge point of the aquifer and has a concentration of about 1.48 mg/L, which is the same as the average concentration in the aquifer. The close agreement between the concentration in the aquifer and the average concentration of all known sources of recharge indicates that there are no other significant sources of nitrogen to the aquifer.

4.7 Model Response to a Constituent Pulse Input

The numerical accuracy of the transport portion of the model was evaluated by comparing model predictions of concentration resulting from a pulse input to the analytical solution derived from mass balance equations. In its simplest form, the model represents the aquifer as a series of completely mixed tanks. If a constant recharge is routed to the Onion cell, then the model is similar to a series of reactors one might encounter in a chemical process. The output concentration of any tank can be calculated by solving the following differential equation:

$$\frac{d(V_i \times C_i(t))}{dt} = Q \times (C_{i-1}(t) - C_i(t))$$

where V_i is the volume of the tank, C_i is the output concentration from the tank, and $C_{i\text{-}1}$ is the output of the upstream tank. This equation was solved for each of the tanks based on a constant rate of recharge to the Onion cell of 50 cfs and a pulse input of constituent resulting in an initial concentration of 1.0 mg/L. A comparison of the numerical and analytical solutions is shown in Figure 4.12. The two solutions for the first four tanks are so close that there is no visible difference between the two. The model prediction for

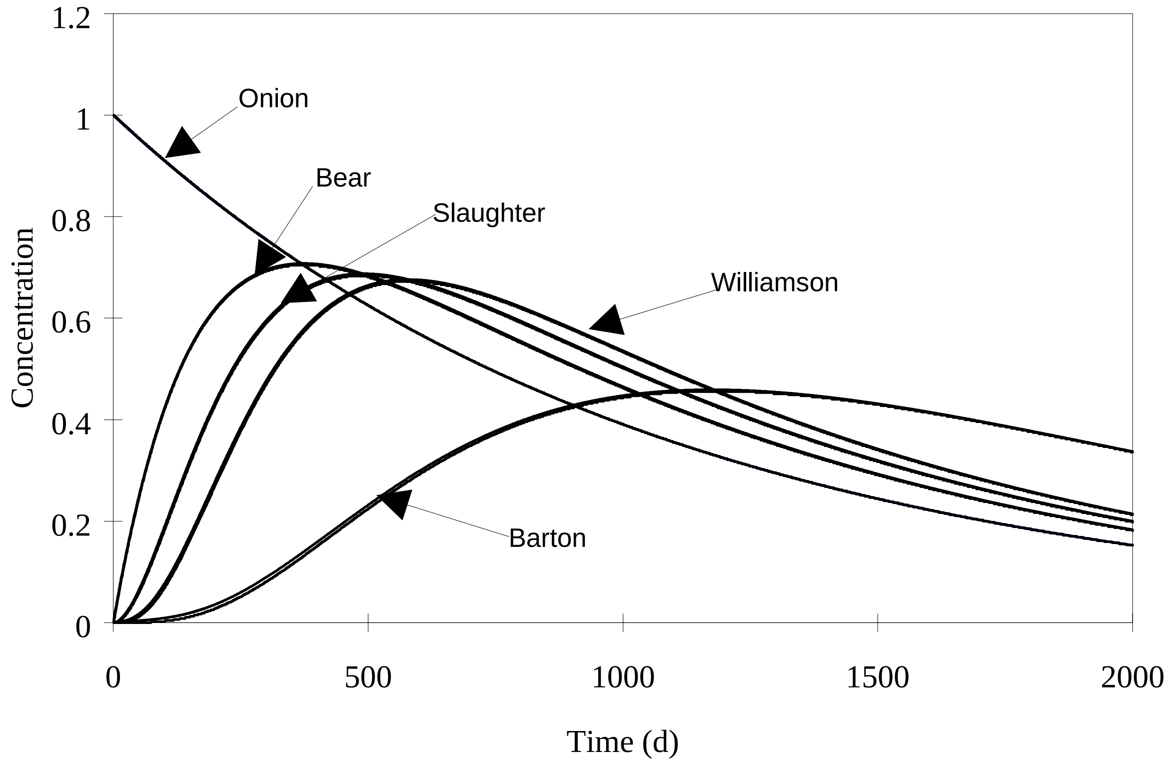

Figure 4.12 Comparison of Numerical and Analytical Solutions for Pulse Input

the Barton cell is slightly lower than the analytical solution at the beginning of the simulation, resulting in the appearance of a slightly wider line, but is not significantly different for most of the simulated period.

In order to examine the response of the model to a more realistic scenario, a pulse input of a soluble constituent was applied to the Onion cell during a historical period when recharge was occurring in all of the cells. The initial concentrations in all cells, and the concentration in diffuse and creek recharge, was set to zero. A concentration of 128.9 mg/L was assigned as the average concentration in Onion Creek on day 701 of the simulation (7/1/81). On this day the maximum recharge rate of 120 cfs was occurring in the creek, resulting in a total mass input to the aquifer of 37,800 kg. This mass is equivalent to 10,000 gallons of a neutral density liquid.

Since the model treats each cell as completely mixed, the mass is instantly diluted by the total volume of the Onion cell, which produced an average concentration in the cell of 0.47 mg/L. Longitudinal dispersion was not included in this simulation. The response of each of the cells to this input is shown in Figure 4.13. The hypothetical constituent appears at the part per billion level in Barton Springs about 65 days later; however, the maximum concentration in Barton Springs (0.12 mg/L) is not reached for about 3 years. The constituent is still present in all of the aquifer cells at part per billion levels at the end of the simulation period, more than 14 years after the initial input.

In general, the effects of dispersion in this model are small because of the extremely low concentration gradients. A pulse input creates the highest gradients one might expect to see in the field; however, the effects of dispersion remain relatively insignificant. Two other simulations were performed, the first with a dispersivity of 141 feet and the second with a dispersivity of 1000 feet. The simulation with the lower value produced essentially the same response predicted when there is no dispersion. The "arrival" at Barton Springs and the maximum concentration occur on the same day, and persistence in the aquifer is unchanged. At a dispersivity of 1000, the arrival occurs at Barton Springs in approximately 30 days, which is about one half as long as the other two simulations. The time until the maximum concentration is reached is unchanged, as is persistence in the aquifer.

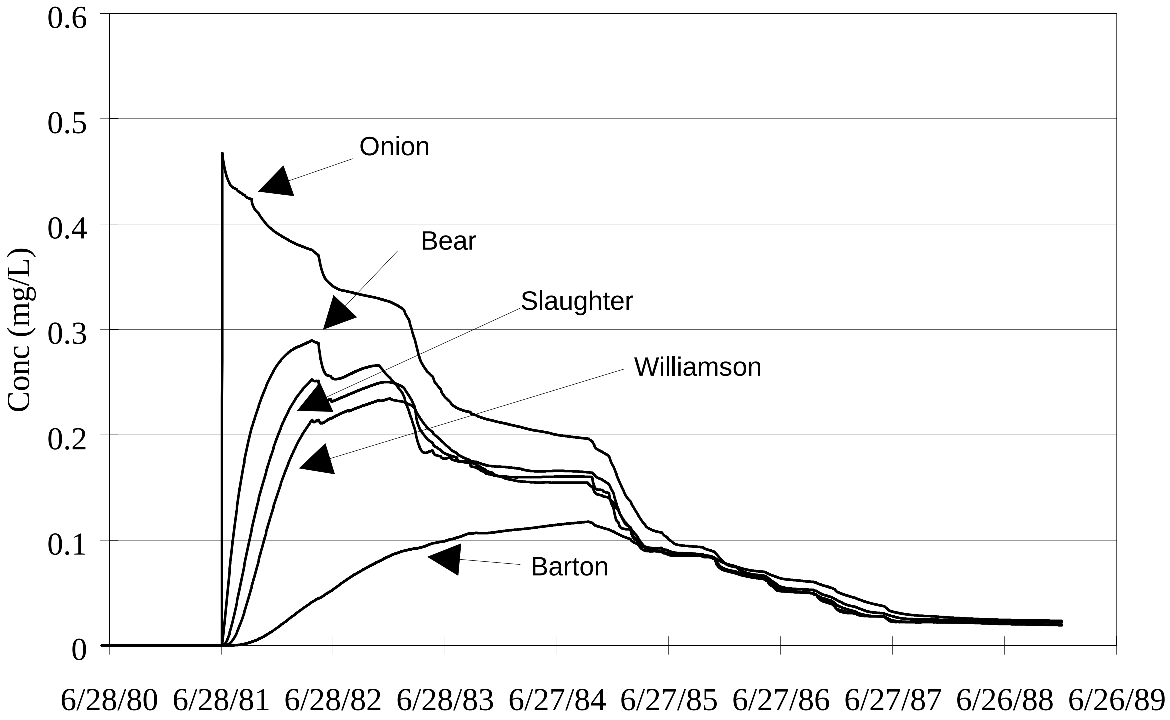

Figure 4.13 Effect of a Pulse Input to the Model

The traditional physical interpretation of a pulse input in a groundwater model is a chemical spill. Because of the coarse spatial representation of the aquifer and the assumption of completely mixed cells, this is not a valid interpretation. The predicted concentrations in the cells and arrival times are functions of the aquifer level at the time of the input, the recharge time series, and the initial mass of the constituent. Therefore, the predicted response is unique to the aquifer conditions and recharge volumes used in this simulation.

5. Estimating the Effects of Urbanization on the Aquifer

The primary goal of this research is the development of a groundwater model which can be used as a tool to evaluate the impacts of urban development on water quality and quantity in the Barton Springs portion of the Edwards aquifer. To predict the effects on the aquifer, one must be able to estimate how urbanization will affect diffuse recharge characteristics and the quantity and quality of water in the creeks supplying recharge to the aquifer.

The goal of this chapter is to show which factors need to be considered and to develop some reasonable model input values which might reflect the impacts of urbanization. Consequently, this is not a comprehensive evaluation of the effects of development, but rather an example of how the model can be used as a management tool. Several arbitrary assumptions were made in the described simulations such as the number of septic systems which might be installed based on a given level of development. A thorough analysis of how development might affect current aquifer inputs was not within the scope of this study.

The best estimates of potential impacts to the surface water systems would ideally be derived using a comprehensive, physically based model which could estimate changes to the creeks supplying recharge to the aquifer. The predictions of the surface water model would then be used as the inputs to the groundwater model to evaluate changes in the aquifer. The City of Austin presently is developing a surface water model for the Barton Creek watershed; however, no research has begun on the other watersheds contributing recharge to the aquifer. Unfortunately, models which are capable of estimating changes in the hydrology of area creeks resulting from urbanization are difficult to calibrate to current conditions much less able to predict future conditions with much confidence.

Rather than waiting on the development of sophisticated surface water models, a simple empirical approach to estimating changes in the recharge characteristics was used to make a first approximation of the magnitude of changes one might expect from a worst-case scenario. In this scenario, the impact of urbanization without the installation of any type of stormwater mitigation was simulated. The fundamental assumption was that urbanization would make the hydrology of the creeks on the contributing zone similar to creeks located in more urban parts of the Austin area. Two scenarios were investigated.

The first envisioned a moderate level of development, resulting in an average impervious cover for the recharge and contributing zones of approximately 20%. This is the level of development which currently exists in the Williamson Creek watershed upstream of the recharge zone. The second scenario envisioned an intense level of development, resulting in an impervious cover of about 45%, which is the current level of development in the Shoal and Boggy Creek watersheds of central Austin. Changes in spring discharge and total nitrogen concentration in the aquifer were predicted based on estimated changes in the hydrology of the creeks and the amount and quality of diffuse recharge.

5.1 Model Inputs for Moderate Development Scenario

The effect of a moderate level of development on the hydrology of the portion of the creeks on the contributing zone was approximated by assuming that all the creeks contributing recharge would have the same rainfall response and water quality as currently exists in Williamson Creek above the recharge zone. The methodology for creating input data for each of the creeks consisted of substituting the Williamson Creek flow record, scaled by the relative sizes of the watersheds, for the measured values of the individual creeks during the simulation period of 8/79-9/94. In addition, the nitrogen concentrations for storm and baseflow conditions of Williamson Creek were substituted for the current concentrations in the other creeks as well. There are essentially no water quality or flood control structures in the upper part of the Williamson Creek watershed, so the model simulation reflects the expected effects of development without stormwater mitigation.

This methodology is easily defended for Bear and Slaughter Creeks, which have approximately the same size watersheds above the recharge zone as Williamson Creek. The Williamson Creek watershed covers an area of approximately 6 mi^2, whereas the areas of Bear and Slaughter Creek watersheds are about 12 mi^2 and 8 mi^2, respectively.

The assumption is not as valid for Onion and Barton Creeks, whose watersheds are much larger than that of the others (124 mi^2 and 107 mi^2, respectively).

Even though it has one of the larger watersheds, Barton Creek generally reaches peak flow rate within 24 hours of a storm event. Samples from Barton Creek at Loop 360 were collected and analyzed for a number of storms during the spring of 1995 to determine the length of time that direct runoff conditions persist in the Creek. Figure 5.1 demonstrates the relationship between runoff and suspended solids concentrations for Barton Creek at Loop 360. This was a fairly large runoff event; however, the maximum flow rate occurred on the same day that runoff began, and suspended sediment concentrations had returned to near ambient conditions within 24 hours of the start of runoff. This behavior is very similar to that of Williamson Creek, so using the Williamson Creek data to infer the future behavior of Barton Creek is reasonable. Future development of the Barton Creek watershed will reduce the time of concentration of surface runoff, making the response even more similar to that of Williamson Creek. In addition, most of the flow (and consequently most of the recharge) occurs under baseflow conditions when the timing of flood peaks and the variation in constituent concentrations are not an issue.

Figure 5.2 shows the expected change in the flow of Barton Creek at Lost Creek Boulevard under these assumptions. The result of a moderate level of development is an increase in the peak flow rates during periods of direct runoff. The number of days of direct runoff also increases because of the larger percentage of impervious cover. The increase in the number of events means that a larger proportion of the recharge will be derived from storm runoff, which has lower water quality. The volume and duration of baseflow show little change in this scenario.

Water quality data from Williamson Creek were used for each of the other four creeks to characterize runoff. An average total nitrogen concentration of 2.79 mg/L was assigned to the water on days when creek flow was identified as being composed primarily of direct surface runoff. Flow on days dominated by baseflow was assigned a concentration of 0.88 mg/L. This substitution of the water quality in Williamson for the

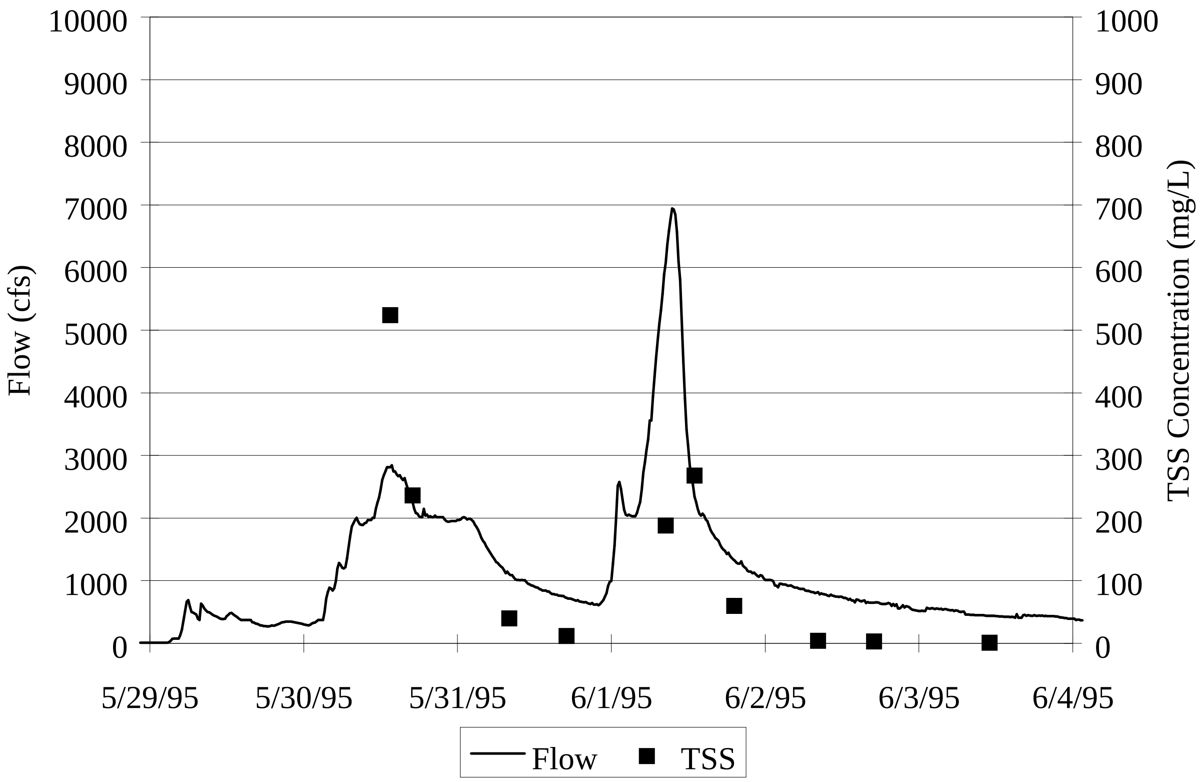

Figure 5.1 Hydrograph of Barton Creek at Loop 360

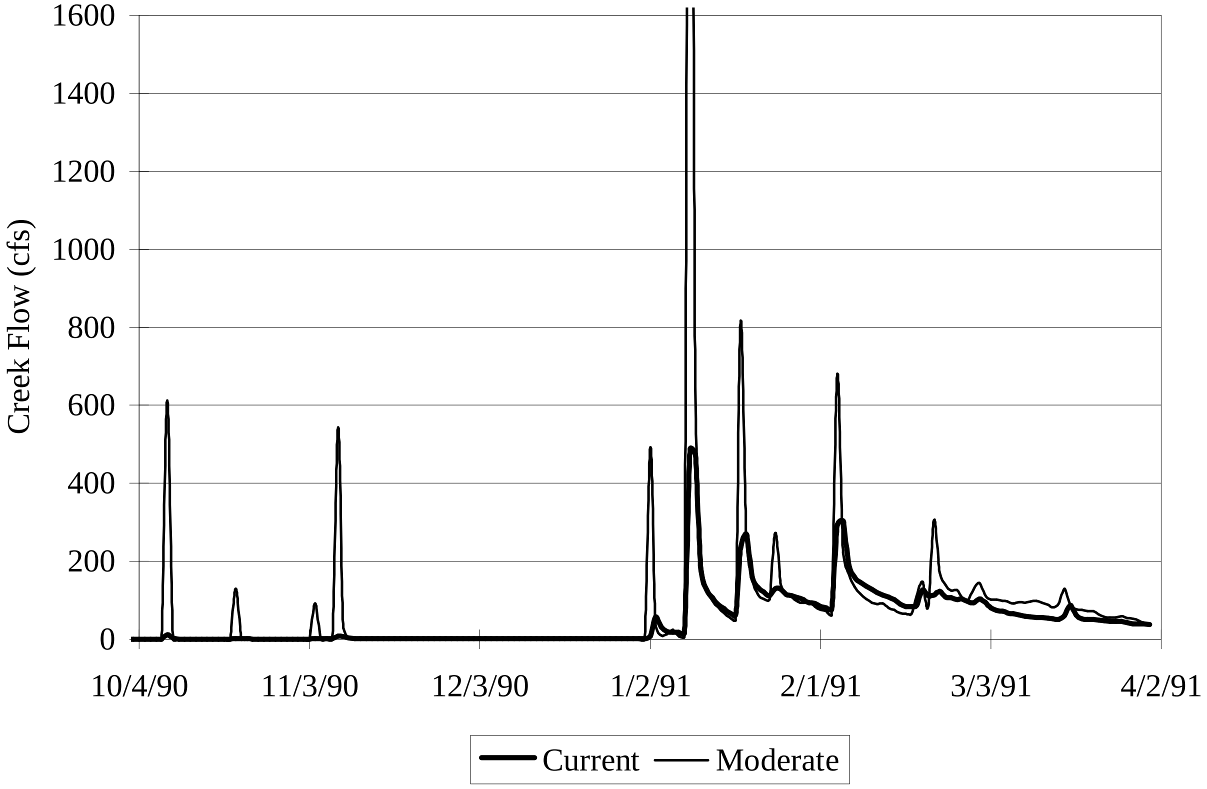

Figure 5.2 Effect of Moderate Development on Barton Creek Flow

other creeks would not be valid for constituents such as suspended solids, of which a significant proportion is derived from the creek channel itself. The higher flow rates predicted for the larger watersheds would have a higher capacity to erode and transport solids than Williamson Creek, so a more sophisticated analysis would be required to estimate loads of solids.

The effect of direct runoff from new development on the recharge zone of the aquifer was not evaluated in this initial simulation. The amount of diffuse recharge was decreased by 20% to account for paving of previously pervious surfaces. There is an extensive system of City of Austin water supply lines and sanitary sewers in much of the recharge zone, so not all new developments would be dependent on septic systems or well water. Because of the current low level of development, some increase in the use of wells and septic systems will probably occur. For the moderate level of development, it was assumed that the number of septic systems and the amount of water withdrawn from the aquifer by wells would be twice the current level. It should be emphasized that this is an arbitrary assumption and not the result of detailed analysis of potential changes which might be expected.

5.2 Model Inputs for Intense Development Scenario

Data from Shoal and Boggy Creeks were used to simulate the hydrology of the creeks under a scenario of intense development. This represents a level of development which is similar to that which exists in the urban core of Austin. The watersheds of each of these creeks have an area of approximately 12 mi^2 above their respective USGS gauging stations, of which about 40-50% is impervious. Many of the same disclaimers apply to this simulation as the previous one. Since these two creeks are larger than Williamson Creek, the issue of scaling the flow by the relative sizes of the watersheds should not loom so large. To create a data file for the same period as the previous simulation, flow data from Boggy Creek for the period 8/79 to 12/83 was combined with Shoal Creek data for the period 1/84 to 10/93 to generate an input file for the simulation period. The input file for each of the five creeks was created by scaling the data from Shoal Creek by the relative sizes of the watersheds.

Figure 5.3 is a comparison of measured flow data during a representative period for Barton Creek at Lost Creek Boulevard with the expected flow after intense development. Although the total runoff for the two data series is almost identical, the temporal distribution is significantly different. The peak flow rates during direct runoff are even higher than those resulting from a moderate level of development, and a higher proportion of the runoff occurs during what would have been extended periods of no flow in Barton Creek. During wet periods, development causes a large reduction in the volume of baseflow relative to current conditions. This results in an even larger percentage of the recharge being derived from lower quality storm flows.

Water quality data from Shoal Creek were used for each of the five creeks to characterize the quality of the runoff. Days when creek flow was identified as being composed primarily of direct surface runoff were assigned an average total nitrogen concentration of 3.72 mg/L, whereas baseflow was assigned a concentration of 1.21 mg/L.

As in the previous case, the effect of direct runoff from development on the recharge zone was not simulated, but estimates were made of the expected change in the characteristics of diffuse recharge and the volume removed by pumping. In this scenario, it was assumed that there was a fourfold increase in the number of septic systems from current levels. The amount of water removed by pumping was also increased by a factor of four. Diffuse recharge from rainfall infiltration was reduced by 40% to account for the increase in impervious cover on the recharge zone.

5.3 Results of Simulation

Changes in the characteristics of the creeks and diffuse recharge result in substantial changes in the water quantity and quality at Barton Springs. Figure 5.4 shows the predicted effect of development on discharge at Barton Springs. The overall effect is a reduction in the average discharge. A moderate level of development resulted in a reduction of approximately 11% from predicted discharge under current conditions. An intense level of development caused a reduction of 34% in predicted discharge. The reduction in spring flow is not uniform, however. Because of the greater number of

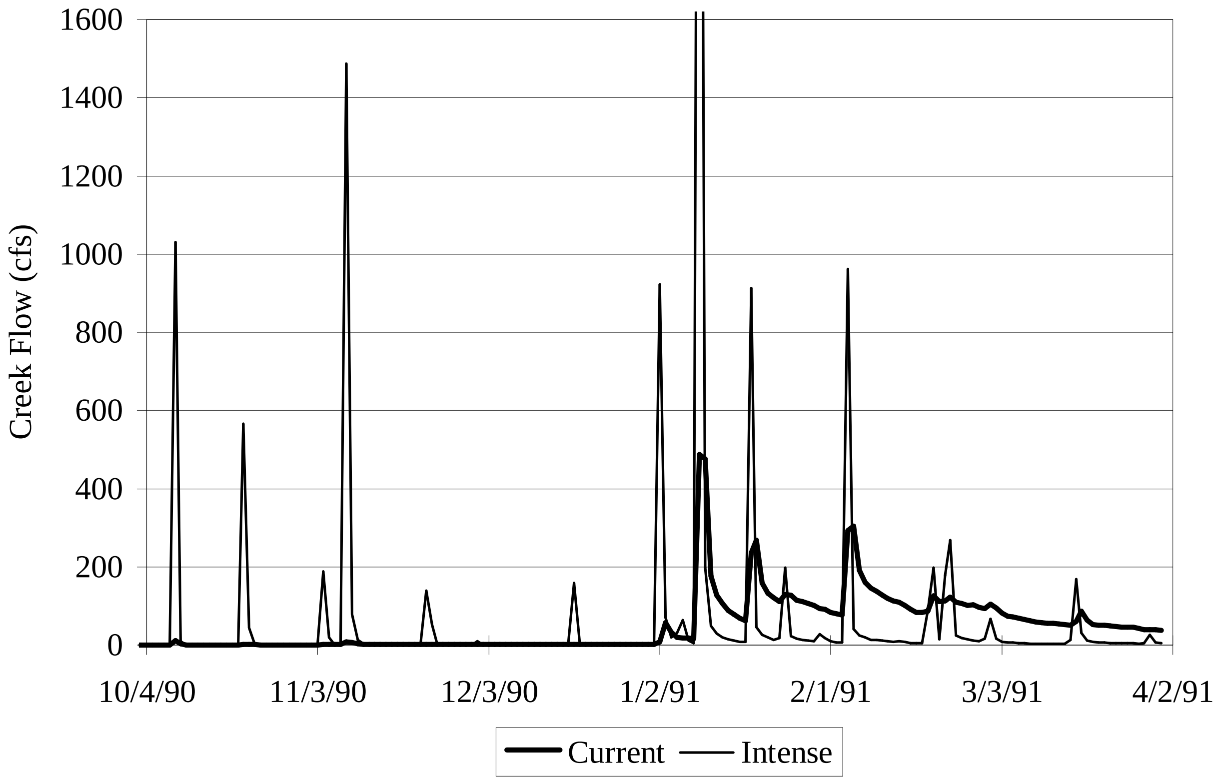

Figure 5.3 Effect of Intense Development on Barton Creek Flow

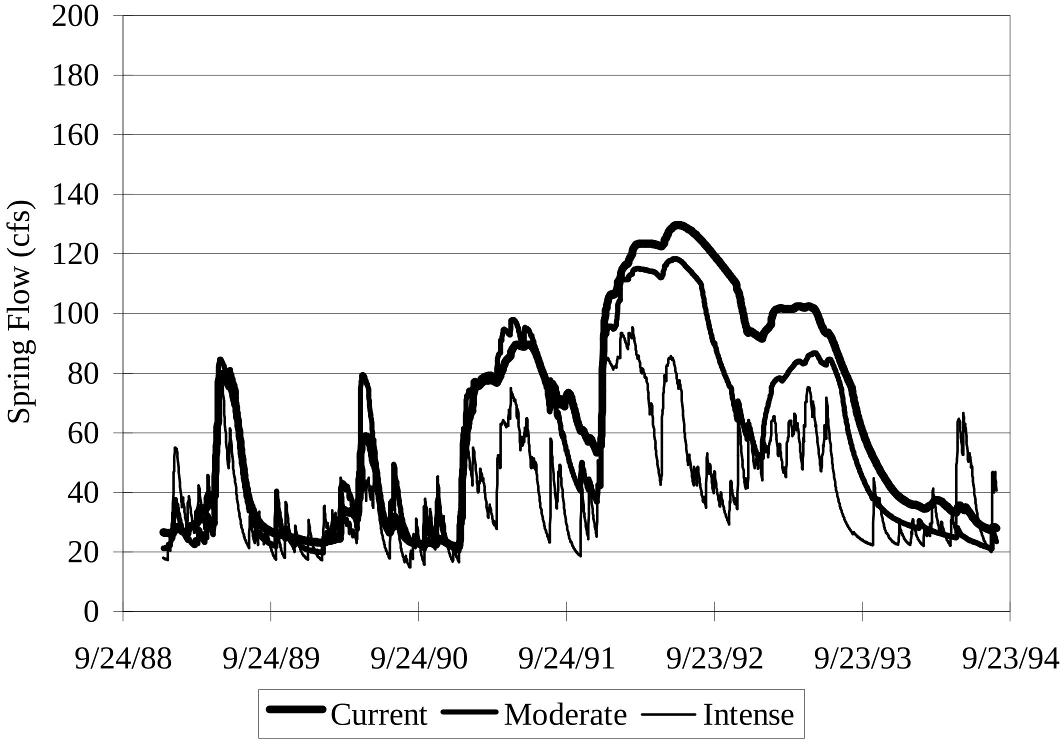

Figure 5.4 Effect of Development on Spring Flow

runoff events during normally dry periods, the minimum spring flows tend to remain approximately the same with development, although the recharge supplying this increased flow is generally lower quality.

The changes in recharge characteristics and increased pumping associated with urban development also reduce the average water levels predicted for each of the cells. The predicted average water levels for four of the cells are shown in Table 5.1. The key well for the Barton cell shows so little variation that the differences between current and future water levels are not meaningful. Although the intense development scenario results in the largest drop in average water level, the change is not uniform. Figure 5.5 shows the predicted change in water level for the Onion cell for the period January 1989 through September 1994. The difference in predicted water levels is largest during extended wet periods and smallest when aquifer levels are low. The maximum difference between current and intensely developed water levels is about 75 feet. At low aquifer levels, the difference between the two is only about 25 feet. This response is similar to that predicted for Barton Springs discharge in that runoff events occurring during dry weather reduce the difference.

Table 5.1 Effect of Development on Predicted Average Water Levels

Cell	Current	Moderate Development	Intense Development
Onion	595	584	556
Bear	555	539	503
Slaughter	512	503	479
Williamson	454	450	444

Increased development also results in an increase in the total nitrogen concentration at Barton Springs. Figure 5.6 shows a comparison of nitrogen concentrations at the Springs for the three simulated scenarios. A moderate level of development resulted in a predicted rise in average concentration from 1.5 mg/L to 1.8 mg/L, an increase of approximately 20%. The average concentration of nitrogen resulting

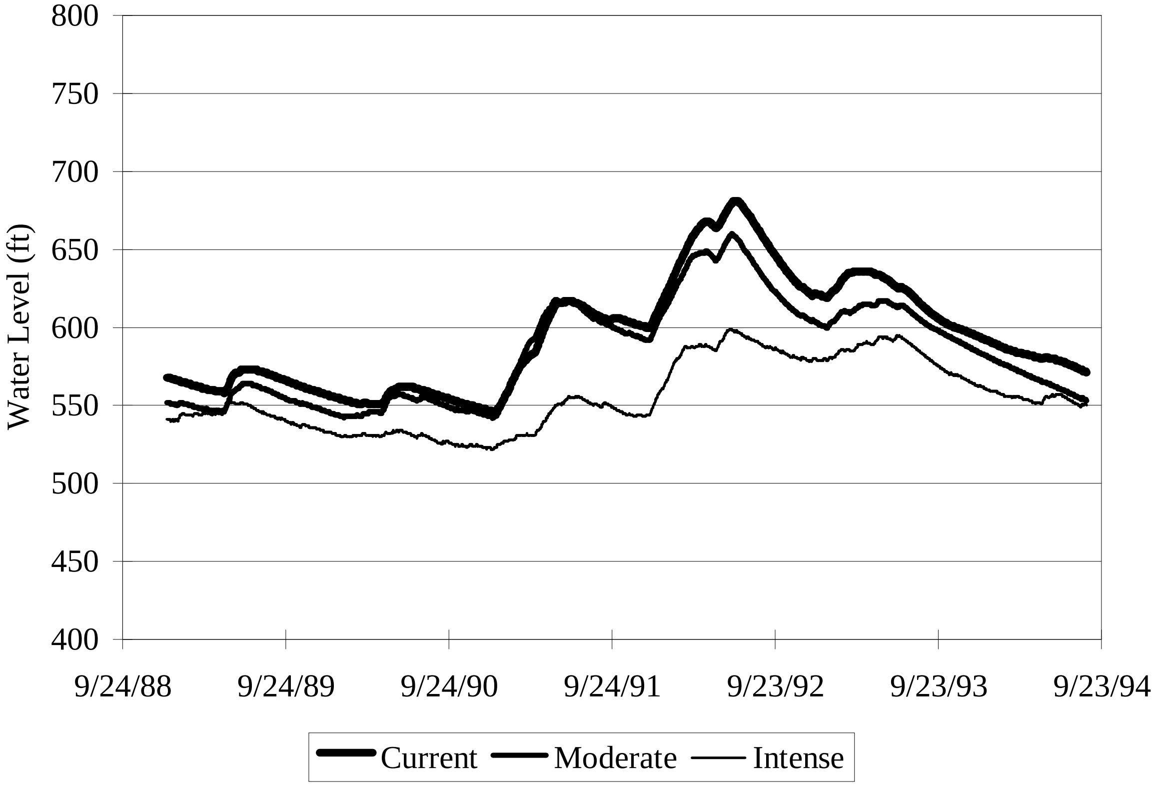

Figure 5.5 Effect of Development on Onion Cell Water Level

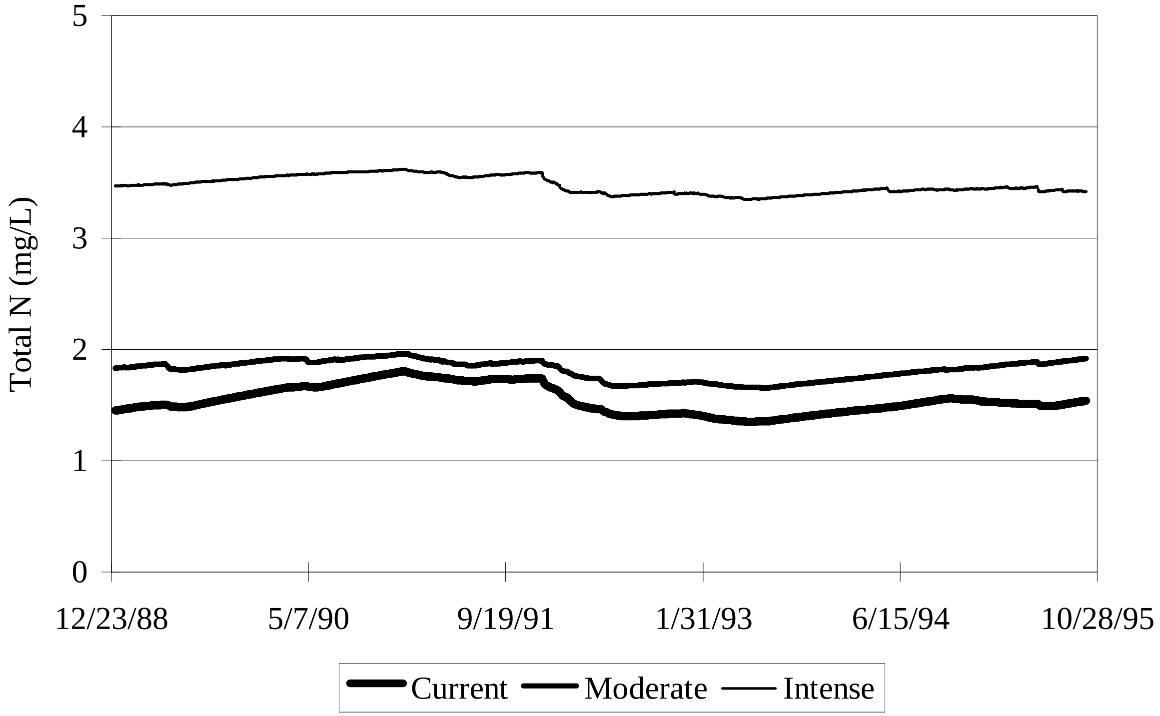

Figure 5.6 Effect of Development on Spring Quality

from intensive development was about 3.5 mg/L, an increase of about 130% from current conditions. The increase was caused by the higher concentration of nitrogen in diffuse recharge (more septic systems), a higher concentration in the creeks supplying recharge, and less creek recharge available to dilute the diffuse recharge.

Similar effects on the average concentrations in other cells were observed for these simulations. Bear, Slaughter, and Williamson cells were predicted to experience an increase in total nitrogen concentration of about 10% as a result of a moderate level of development and 100% as a result of intense development. For most of the aquifer, nitrate concentrations will remain far below current drinking water standards (10 mg/L as N), even after intense development of the areas contributing recharge to the aquifer; however, a few areas may exceed these standards. In particular, the area shown in Figure 4.6 between Slaughter Creek and Williamson Creek has consistently had much higher concentrations than the aquifer as a whole. Increases of the magnitude predicted under the intense development scenario could result in concentrations which exceed drinking water standards in this area. Figures showing the effect of development on the quality and quantity of water in each of the cells are contained in Appendix C.

Septic systems currently supply only about 10% of the nitrogen input to the aquifer. An analysis of the effect of increasing the number of septic systems on the recharge zone was conducted under the assumption that development density would be too low to affect water quality in the creeks or the amount of diffuse recharge. This assumption is reasonable for small changes in impervious cover resulting from the additional development. The results of this analysis are shown in Figure 5.7, which shows the average concentration at Barton Springs as a function of the number of septic systems. Because of the current low concentration of nitrogen in the aquifer and the relatively small changes resulting from an increase in conventional septic systems, the number of systems in the recharge zone can be increased significantly from the current number of 5900 without creating significant water quality problems or additional health risks.

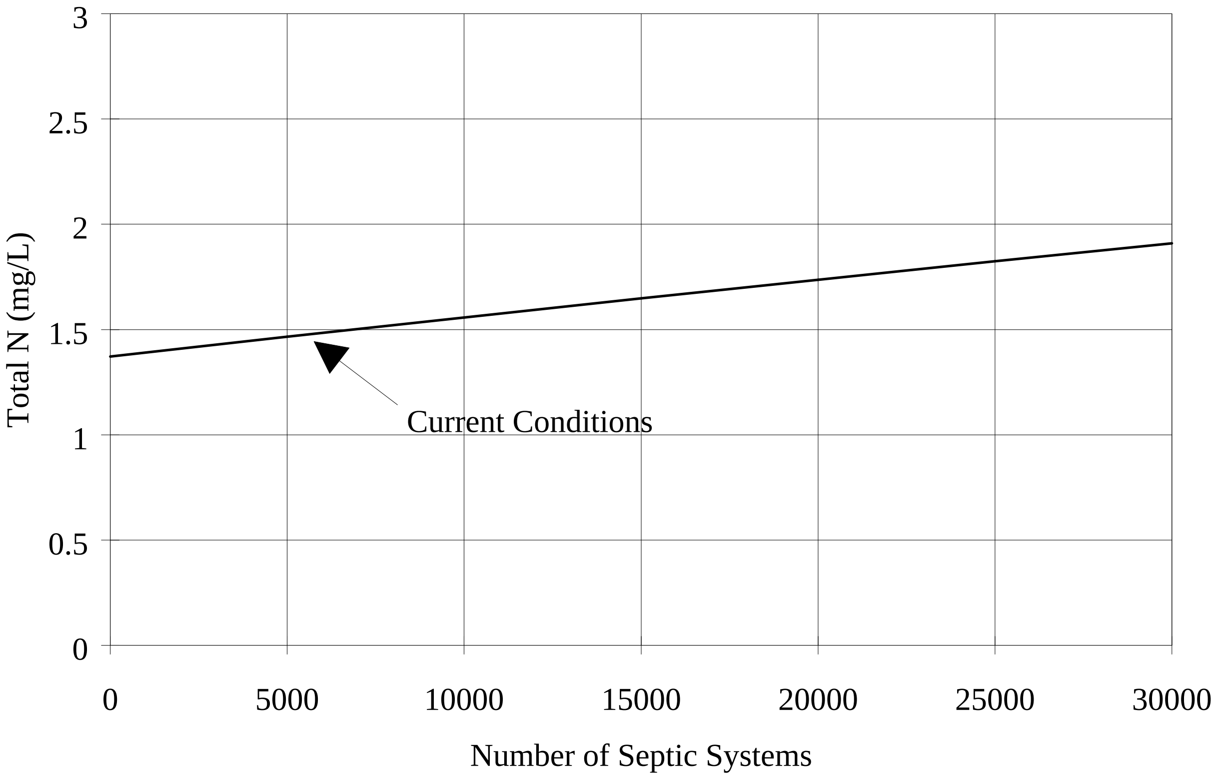

Figure 5.7 Impact of Septic Tanks

5.4 Modeling Other Constituents

A similar analysis could be made for other soluble constituents of interest. The most difficult part of the evaluation is quantifying the sources and loads and determining how urban development will affect the diffuse and creek recharge concentrations. Many other constituents of concern are not conservative and may decay in the aquifer, thus requiring the identification of the variables controlling reaction kinetics. In addition, as pollutants migrate through the beds of the creeks or through soil zones, their concentrations may be attenuated by filtration, adsorption, or decay before reaching the aquifer. Developing input files for the model is therefore a complex task.

Since almost all pollutants occur in higher concentrations in storm runoff than in baseflow, the changes in the hydrology of the creeks associated with development can be expected to produce some degradation in the water quality of the aquifer. These changes may be mitigated to some extent by the use of appropriate storm water controls to treat runoff from new developments.

Some concern has been expressed about the increase in sediment in the creeks due to construction runoff, runoff from pervious surfaces, and channel erosion resulting from increased flow rates in the creeks. Increases in turbidity and suspended solids concentrations at Barton Springs are associated with flood flows in Barton Creek, indicating at least some transport of solids within the aquifer. The increase in turbidity in Barton Springs Pool on these days results in pool closures when visibility is reduced to less than four feet. Analysis of solids which have accumulated in well bores and water supply tanks of municipalities indicates that there is no long-range transport of surface-derived sediment. The solids in these wells consist almost exclusively of euhedral dolomite crystals derived from within the aquifer (B. Mahler, personal communication, 1996).

Although the model developed cannot be used to directly predict changes in solids concentrations at the Springs resulting from development, a few qualitative statements can be supported based on the model’s predicted flow rates for Barton Springs. The predicted spring discharge in the intense development scenario (Figure 5.4) is much more variable because of the increase in the number of recharge events associated with the increase in impervious cover. Continuous water quality monitoring of the Springs demonstrates an increase in turbidity associated with storm flows in Barton Creek. Barton Springs Pool is closed when the turbidity prevents lifeguards from having a clear view of the pool bottom. Based on the association of runoff events and pool turbidity, the increase in the number of recharge events predicted by the model will result in more frequent pool closures as the level of development increases.

6. Conclusions and Recommendations

6.1 Conclusions

The goal of this study was the development of a regulatory tool to assess the effectiveness of various management strategies for preventing the degradation of the Barton Springs portion of the Edwards aquifer. Three important tasks were required to accomplish this goal. A parsimonious model was formulated which has the ability to accurately predict water movement in this complex karst aquifer. To calibrate the transport portion of the model, the sources and quantities of nitrogen supplied to the aquifer were evaluated. This included a method to estimate current nitrogen load derived from septic systems and predictions of the water quality impacts of a continued reliance on these on-site systems for wastewater treatment. Finally, a simple approach for estimating urbanization-induced changes in the surface water systems supplying recharge to the aquifer was used to estimate potential changes in water quantity and quality in the aquifer. Model simulations with these new inputs were used to predict the degree to which development might reduce the quantity and quality of water recharged to the aquifer. Recommendations for changes in the monitoring programs are also made based on the results of the model development. These changes could provide data to improve the performance of the current model and lay the groundwork for the development of more spatially detailed models.

This study developed a new type of lumped parameter model for the Barton Springs portion of the Edwards aquifer. The aquifer was divided into five cells, each of which is treated as a tank with a single well used to characterize conditions in the cell. This model differs from previous models in that it allows properties within the cell to vary with water elevation. Because movement of water within cells is not considered, the model retains the lack of a spatial dimension characteristic of lumped parameter models. The model is capable of predicting regional water levels, spring discharge, and aquifer water quality. A comparison of model predictions with historical data for the period August 1979 - September 1995 demonstrates its accuracy. This simple representation of the hydrologic system produced accurate results with fewer data requirements and calibration parameters than traditional groundwater models.

This model appears to be successful because the majority of the Barton Springs portion of the Edwards is unconfined. Because of the horizontal stratification of the formation, vertical changes in aquifer properties have a greater influence on aquifer behavior than does horizontal variation. As water levels rise, caves, conduits, and other stratigraphic features that become submerged strongly affect flow and storage in the aquifer. The wide range of water levels that occur in this aquifer appear to amplify these differences in flow and storage characteristics. This novel approach should prove effective for the analysis of other karst systems as well.

When faced with the task of modeling an extremely complex flow system, the natural tendency is to develop a more complex model. However, this research shows that a very simple model can provide useful information about the behavior of such a system. In addition, the model explicitly acknowledges the lack of detailed knowledge about the location of conduits and other flow paths by predicting only regional effects. While predictions made by more complex models are often given more validity by persons unfamiliar with their use or development than might be warranted–especially true when the values of physical parameters such as specific yield or hydraulic conductivity may have been estimated from a sparse data set–this parsimonious model provides a useful management tool that is easy to use and understand, and whose predictions are not as subject to misinterpretation as those of a complex distributed parameter model.

In a quality assessment, this study found that the water quality of Barton Springs has remained essentially unchanged over the last 15 years. None of the constituents monitored by the USGS showed any significant long-term variation other than total nitrogen. Although urbanization of the watersheds contributing recharge to the aquifer is proceeding at a rapid rate, the overall change in impervious cover during the study period is still fairly small. Impervious cover in the contributing and recharge zones probably accounts for only 5-8% of the total area. Small changes in water quality associated with this level of development are difficult to document because of the amount of variation inherent in storm runoff. Most of the variability in concentration observed at Barton

Springs is short term and associated with the beginning of recharge events, while the quality of most of the spring discharge is very constant. This model was developed to predict the impacts of urban development on the aquifer. As such, the use of a large cell size to evaluate the impact of widespread nonpoint source pollution is appropriate; however, this formulation precludes the prediction of short-term variation.

Verification of the transport capability of the model was conducted using total nitrogen. This constituent was originally chosen because concentrations at Barton Springs showed significant variation. For example, during the summer of 1982, concentrations at the springs were approximately double the values recorded both before and after; however, analysis of water quality data collected from wells and creeks during 1982 did not support a finding of widespread changes in aquifer quality. These higher concentrations appeared to be the result of leaking sewer pipes near Barton Springs (Slade et al., 1986). Nevertheless, nitrogen was still an attractive choice for transport modeling because it is soluble and conservative and because of the concern about the effect of additional septic tanks in the recharge zone. In addition, nitrogen concentrations are commonly measured during routine sampling of wells and the springs.

Modeling nitrogen concentration in the aquifer required the identification and quantification of known sources. Concentrations in the creeks over the recharge zone were estimated from USGS sampling data for both baseflow and direct runoff conditions. The amount of nitrogen in diffuse recharge was estimated using a computer model (GLEAMS) which predicts nutrient uptake and transport in the unsaturated zone. Simulation of transport of nitrogen in the aquifer using the estimated input parameters successfully reproduced the concentrations measured at Barton Springs. The predicted concentration distribution in the aquifer also was similar to measured values.

The potential effects of urban development in the areas supplying recharge to the aquifer also were investigated. The expected changes in the hydrology of the creeks were estimated by comparison with other creeks in more developed parts of the Austin area which lack significant numbers of stormwater runoff controls. Development reduced the baseflow while it increased the peak flow rates during periods of direct runoff. These changes reduced the amount of recharge to the aquifer, lowering the average discharge of

Barton Springs. The reduction in spring flow was not uniform, but was more apparent during periods of greater recharge. The increase in impervious cover of the watersheds resulted in more recharge during what would normally have been extended periods of no recharge so that the average minimum spring discharge remained unchanged.

Unless urban development on the recharge zone dramatically increases the amount of water pumped from the aquifer, there is little danger that Barton Springs would cease to flow. Changes in the hydrology of the creeks caused by urbanization tend to increase the relative amount of recharge which occurs during extended dry periods. In addition, almost all of the pumping currently occurs in the Onion and Bear cells, which are farthest from the Springs. Large increases in water use in this area are likely to create problems related to lower water levels in the Buda and Manchaca areas, which could periodically cause some wells to dry up. The areas closer to the Springs are generally served by the City of Austin municipal system, and increased pumping in these areas is highly unlikely. Recharge from Barton Creek, which accounts for about 30% of total creek recharge, will continue to discharge at the Springs regardless of changes in water use in other parts of the aquifer.

Large areas in the western portion of the aquifer do not have the large changes in water levels experienced in the eastern portion. This indicates that the western portion generally has lower hydraulic conductivity, a situation which would not support high demand water wells. Given the existing water infrastructure, the City of Austin municipal system will likely be the source of drinking water for any large-scale developments in this area.

Increased urbanization will likely reduce the quality of the water recharged to the aquifer. The simulation of nitrogen transport in the aquifer was used to demonstrate how the model can be used to estimate the impact of development. Many other pollutants are present in storm water runoff and the effect on the aquifer of an increase in their concentrations was not evaluated in this study. Other constituents which may be of concern include metals, hydrocarbon compounds, pesticides, and oxygen demanding materials. Increases in the concentrations of these pollutants may have a larger impact on public health and aquatic life than that shown for nitrogen. However, only the effect of urbanization on nitrogen concentrations was estimated as part of this research.

It was shown that the average concentration of nitrogen in creeks was higher for both baseflow and direct runoff in areas of Austin with more impervious cover. Using the data from more urban creeks, a level of intense development was estimated to raise the predicted nitrogen concentration at Barton Springs from about 1.5 mg/L to approximately 3.5 mg/L. Average concentrations in the aquifer are predicted to experience similar percentage increases. These increases are predicted to be the result of changes in the land use of the area watersheds from predominately undeveloped/rural to residential/commercial at a density similar to that which exists in the Shoal Creek watershed. In the model scenario, this level of development was assumed to occur over the entire recharge and contributing zones, more than 300 mi^2. Even at this level of development, changes in nitrogen concentration in the aquifer would not be noticeable by most users. Because of the generally low nitrogen concentration at the current time, drinking water standards will not be exceeded in most of the aquifer; however, concentrations in some local areas such as Sunset Valley may become a concern. Septic systems account for only about 10% of the nitrogen in the aquifer so an increase in their use should not be a problem unless development reaches a level where storm water runoff from these sites reduces the quality of the water in the creeks as well. The greatest impact may be on Barton Springs Pool and Town Lake, where the increased nutrient supply will promote the growth of algae and euthrophication.

The data used to create the input files were estimated from creeks which have only small numbers of storm water treatment systems in their watersheds. Unfortunately, the current systems required by the City (sedimentation/sand filtration) only reduce nitrogen concentrations by about 20%; therefore, the predicted increases in concentration may occur even if development includes storm water controls built to current standards.

Water in the aquifer moves from south to north, and the general direction of flow does not appear to be affected by potential changes in the hydrology of the creeks or increases in the number of water wells. This means that the water quality in the aquifer between the towns of Buda and Kyle (the Onion cell) is controlled exclusively by the quality and quantity of recharge in Onion Creek. Changes in land use in other watersheds will not have a significant effect on either quality or water levels in this area of the aquifer. The quality in other areas of the aquifer is determined not only by the creek supplying recharge to that area, but also the quality of water in the creeks to the south of the particular area. For instance, water quality in the Manchaca area is a function not only of water quality in the Bear Creek watershed, but in the Onion Creek watershed as well. Therefore, changes in recharge quality in Onion Creek will affect the quality of the entire aquifer and of Barton Springs. Conversely, changes in water quality in Barton Creek will affect only areas north of Sunset Valley.

Changes in land use in the Barton Creek watershed are most likely to be evident at Barton Springs Pool. The entire area of the Barton cell is served by the City municipal water system, so there is only minimal groundwater use in this area. Changes in water quality in the Pool will probably be larger during recharge events than the average change predicted by the groundwater model. This is because the recharge from the creek is not thoroughly mixed with the water in the aquifer. This conclusion is supported by the rapid changes in water quality measured at the Springs at the beginning of recharge events. The increase in impervious cover in the Barton Creek watershed will result in more recharge events that will have the capacity to alter water quality at the Springs. Increases in suspended solids and turbidity associated with these events will probably lead to more frequent pool closures. Because storm recharge from Barton Creek has a lower nitrate concentration than the aquifer as a whole, the nitrate concentration in the springs is reduced during recharge events; however, this relationship may change if development raises the concentration of nitrogen in the creek. The relationship between the concentrations of other constituents in Barton Springs and recharge events needs a more thorough evaluation.

Implications for the Rule-Making Process

In an idealized setting the rule-making process can be divided into three major activities: monitoring, model development, and scenario evaluation. The goal of the monitoring phase is to establish the existing conditions of the system, which in this case is information on the quantity and quality of water in the creeks and aquifer. Monitoring can also be used to document changes in the systems which occur as a result of development or other activities. In addition, monitoring can be used to establish the performance of various storm water runoff control structures which might be required by future regulations.

An important aspect of model development is the analysis of the monitoring data to establish which processes are important in determining how the hydrologic system operates. Simplified representations of these processes are then incorporated into a physically based mathematical description of the system. Monitoring data is then used to verify the representation of the system and to determine calibration parameters of the model. Since the model parameters have a physical basis related to properties such as impervious cover (surface water models) or hydraulic conductivity (groundwater models), one can estimate new model parameters based on expected changes to the system (i.e., changes in land use).

In scenario evaluation, one could alter the calibrated model to investigate the effects of potential impacts to the hydrologic system. The physically based parameters of the model could be varied to explore the expected effects of a specific development. Various storm water control strategies then could be explored with the model to determine their expected overall effectiveness for achieving goals such as non-degradation or no impairment of beneficial use. The chief concern at this stage of the process is the reliability and accuracy of the model under conditions other than those for which the model was calibrated.

Development of the groundwater model for the Barton Springs portion of the aquifer illustrates a number of problems associated with each of these idealized major activity phases. In general, water quality monitoring is only detailed enough to approximately establish the current conditions of the system. Storm water monitoring is based on the collection of discrete samples over a period of time, so laboratory error and natural variation in water quality combine to produce a situation where the exact state of the hydrologic system never can be perfectly known. This limitation is more severe in water quality sampling because the expense of analyzing numerous samples is prohibitive, whereas water quantity measurements can be made nearly continuously at little cost once a gauging station has been installed.

During model development, the monitoring data are analyzed to determine how the system functions. Because of inherent limitations in the detail and accuracy of the monitoring data and because of the essentially infinite number of factors which may influence water quality, the final model is an simplified representation of an imperfectly known system. Therefore, models are always wrong in the detail, but may reproduce the general behavior of the system. Even physically based models, whose parameters have been measured in the field, are not likely to approximate the measured response of the hydrologic system without additional parameter “adjustment,” which constitutes the calibration process. The final result of a successful modeling effort is a simplified representation of the system which is neither unique nor exact. This means that a different model can always be developed which does a better job of reproducing the measured behavior of the system. The decision about whether a given representation is adequate depends primarily on the objectives and intended uses of the model.

In the final step of the rule-making process, the calibrated model would be used to evaluate various regulatory options, including types and design of storm water control systems. To do so, one would take the model calibrated for current conditions and vary the parameters to assess the impact of development and then determine how the different runoff control systems might mitigate predicted impacts. In the case of a surface water model, one might want to investigate the potential impact of full development in the Barton Creek watershed. In order to accomplish this, one would be required to replace the calibrated parameters with those appropriate for the future condition. Unfortunately, there is no way to evaluate the accuracy of the new model predictions. This results in potentially large errors in estimating the effect of development and the efficiency of the proposed control strategies. Therefore, there will always be a degree of uncertainty (probably large) about whether the right policies have been implemented.

To achieve the best possible results, all three steps in the process (monitoring, model development, and scenario evaluation) must be successful. A monitoring program is required that can supply the appropriate data for model development. The limitations and uncertainty inherent in the modeling process should be clearly stated and objectives developed which are compatible with model capabilities. In addition, the development of input files and new parameters to model potential impacts requires a thorough knowledge of the model assumptions, model limitations, and the physical processes involved.

This groundwater model is a very simplified representation of the physical system, but the detail is appropriate for the amount and type of data available for calibration. Furthermore, only the simplest surface water models are available to supply the input files needed to simulate the effects of urban development. As more data become available, more accurate groundwater models for the Barton Springs portion of the Edwards aquifer will be developed. A number of changes in the current monitoring programs operated by the City of Austin and other agencies could help improve the performance of this model or lead to the development of new models.

6.2 Recommendations

The development of a model for the Barton Springs portion of the Edwards aquifer has resulted in the identification of a number of areas where additional data could improve model performance and capabilities. Changes in both surface and groundwater monitoring would be required to achieve the optimum results from the model developed here. Additional monitoring will also be required to develop models with more spatial detail or the ability to predict the impacts of accidental spills or other point sources of pollutants.

6.2.1 Surface Water Monitoring

Calculations of recharge quantity and quality have been based on measured values of flow and quality of the creeks crossing the recharge zone. To improve the predictions of the current configuration of the model, it is recommended that additional stream flow gauging stations be established to better estimate the location, quantity, and quality of recharge.

1) Install a monitoring site on Barton Creek just upstream from Barton Springs Pool.

Barton Creek is the second largest source of recharge to the aquifer based on flow measurements recorded above the recharge zone (Lost Creek Boulevard) and at a point located approximately half-way across the recharge zone (Loop 360). The most critical information which could be developed for this creek is the relationship between the creek and aquifer in the section of the creek between Loop 360 and Barton Springs Pool. The flow behavior in this stretch of the creek is critical for accurate calibration of the model.

During low water levels in the aquifer, recharge apparently occurs along the entire length of Barton Creek over the recharge zone, but during high water levels the stretch below Loop 360 receives discharge from the aquifer as baseflow. Since the farthest downstream gauge is located at Loop 360 near the center of the recharge zone, there are no accurate data that relate recharge behavior in this stretch to water levels in the aquifer. In addition, this is the most highly developed area in the Barton Creek watershed and presumably has the lowest water quality. It is recommended that a stream monitoring station be installed just above the Barton Springs Pool or in the creek bypass. Water quantity measurements would document the relationship between the creek and aquifer. Periodic water quality monitoring at this site also could demonstrate the effect of intense development on the water quality of the creek.

If the amount of recharge occurring in the lower section of Barton Creek were known, it might be possible to incorporate this information in a future version of the model which would allow some of the recharged water to discharge at the Springs without being mixed completely with the water in the aquifer. This would result in a more rapid increase in spring discharge and create the short-term variability in water quality observed during recharge events. Preliminary investigation of a six-cell model (the five creeks and a cell for Barton Springs), indicates that accuracy can be improved and that calibration parameters would then assume more physically realistic values for cells near the springs.

2) Move Williamson Creek monitoring site to the upstream edge of the recharge zone.

The groundwater model was developed and calibrated using flow data for this creek collected at Highway 290, which is located at the upstream edge of the recharge zone. The monitoring station at this site has been discontinued and replaced with a station at Brushy Creek Road, which is located approximately halfway across the recharge zone. This should not affect water quality inputs for the groundwater model, but will result in underestimating water quantity because much of the flow is lost to recharge before reaching the gauging station. Because Williamson Creek contributes the least amount of recharge of any of the creeks, errors caused by using the data from the existing station will not be large.

3) Install temporary monitoring sites on Little Bear Creek to better establish water quality and recharge behavior.

There are currently little data on flow and recharge for Little Bear Creek. According to Slade et al. (1986), this creek has approximately the same flow and recharge characteristics as Bear Creek, so for the model simulations, the flow and estimated recharge on Bear Creek was doubled to account for the contribution from Little Bear Creek. Based on this analysis, the two creeks were lumped into a single cell in the groundwater model. Together the two creeks account for approximately 14% of the creek-derived recharge.

There are significant differences in the watersheds of the two creeks, so one might expect their behavior also to differ. The entire watershed of Little Bear Creek lies within the recharge zone, whereas a significant portion of Bear Creek lies on the contributing zone. One might therefore expect less flow in Little Bear Creek. The establishment of temporary stream gauging stations on Little Bear Creek would be useful for establishing the relationship between runoff in Little Bear and Bear Creeks and for estimating the amount of recharge that occurs. The quality of recharge from Little Bear Creek is not very well established. The concentrations of nitrogen used in the simulation were based on only 10 measurements collected during a 15-year period. With the variability inherent in stormwater quality, this is not a sufficiently large sample to accurately establish recharge quality.

4) Determine recharge characteristics for specific stream segments within the recharge zone.

The current configuration of the groundwater model is suitable for calculating the effects of storm water runoff from development occurring on the contributing zone. It is also capable of including changes in diffuse recharge characteristics caused by development on the recharge zone; however, the effects of storm water runoff from the recharge zone cannot currently be modeled. Two additional requirements for expanding the capability of the model to include these effects are a calibrated surface water runoff model for the recharge zone and more detailed information about the recharge rates in various segments of the creeks.

The current understanding of recharge rates is based on paired sets of measurements taken above and below the zone. This allows the identification of the average recharge rate per stream mile. If one desired to model the impact of a proposed development near the downstream edge of the recharge zone, information about the relationship between flow and recharge for the segment located between the proposed development and the downstream edge would be required. Modeling of the effect of development at an arbitrary location on the recharge zone would first require detailed flow loss studies of each of the creeks, which would identify recharge rates with specific stream segments. The data needed to develop the recharge runoff relationship would have to be collected from several stations on each creek over a period of time that included a wide range of creek flow rates. This would require the establishment of temporary stream gauging stations and creation of rating curves for each of the sites. A large financial and manpower commitment would be required to develop this data. There is some question whether the information developed would result in a model with significantly improved capabilities, so the advantages should be examined in light of the goals and objectives of the City of Austin.

6.2.2 Groundwater Monitoring

5) Estimate Barton Springs discharge from a well located farther from the pool.

USGS estimates of Barton Springs discharge are based on water levels in well YD-58-42-903 located adjacent to Barton Springs. The results of this study show that the water levels and predicted discharge are highly dependent on the water level in the pool. Erroneous measurements occur when the pool is lowered for cleaning or when flows in Barton Creek exceed the capacity of the bypass channel. Current operation of the pool includes nightly draining for cleaning and maintenance activities which severely reduces the accuracy of the estimated discharge. The City should consider requesting that USGS use a well further from the pool to estimate discharge from Barton Springs. Slade et al. (1986) demonstrated that there is a linear relationship between spring flow and water levels in much of the aquifer, so there are probably a number of wells which could be used. Well YD-58-42-915, which is located near the intersection of Rabb Road and Rundell Place approximately one half mile south of the current well, might be the best choice. This well also responds to changes in the pool water level but not to the degree of the current well. Using this well to characterize the Barton cell in the groundwater model would also increase model accuracy for predicting water levels in the Williamson Cell by providing a wider range of water levels to relate to flow.

6) Monitor daily water levels in a well located near the intersection of Manchaca and Slaughter Lane.

Water levels are not very well established for the area represented by the Slaughter Cell. There is currently no well with daily water level measurements as there are for the other four cells. The BS/EACD is monitoring water levels in a well located near the Circle C development in the Slaughter Creek watershed. Unfortunately, this well maintains a constant water level except during periods of relatively high levels in the aquifer; consequently, this well does not seem to have a good hydraulic connection to the main portion of the aquifer. The City should encourage BS/EACD to seek an alternate well for monitoring. The optimum location for such a well would be near the intersection of Manchaca Road and Slaughter Lane.

7) Evaluate source of persistent high nitrogen concentration in the Slaughter cell.

During the course of the nitrogen study, an area of persistently high concentrations of total nitrogen was identified between Slaughter and Williamson Creeks. This area should be subject to further evaluation to determine whether there is large area of high concentrations or whether the single well (YD 58-50-406) has an isolated problem such as a bad casing or is in the center of a small, localized source. Testing for the presence of fecal coliform or other indicator bacteria in the well and general vicinity might also be warranted. If overall concentrations of nitrogen in the aquifer increase due to a greater number of septic systems, reduction in quality of the creek water, or other reasons, this area of high concentration may pose a threat to the drinking water quality of Sunset Valley, located immediately down-gradient of this area.

8) Increase frequency of water quality sampling in wells and at Barton Springs.

Monitoring the water quality of Barton Springs and of wells in the aquifer should continue so that changes in water quality can be identified at the earliest possible time. Because of the natural variability demonstrated by the historical data, a large number of samples will be required for timely identification of long-term changes in water quality. Sampling of wells on an annual basis will not be sufficient. A groundwater sampling scheme should be developed based on an analysis of the historical water quality data. The number of samples required in a future monitoring program is a function of the variability in the existing data, the magnitude of change that one might want to identify, and the length of time before a statistically significant number of samples could be collected under the proposed plan. As an example, under the current Barton Springs water quality monitoring plan, a change in the average nitrogen concentration in the aquifer resulting in a doubling of concentration would not be identified for several years based on collection of approximately five samples per year. Smaller changes would take even longer to recognize statistically.

9) Develop data on flow paths, travel times, and other pollutant transport properties for future use in a more detailed groundwater model.

The current model was developed to evaluate the impacts of nonpoint source pollution in the aquifer. As such, the assumptions were made that the impacts would be widespread and persistent and that the input of pollutants associated with development would occur over a wide area of the aquifer. Once developments were established, the inputs of pollutants were expected to continue indefinitely into the future. In addition, flow paths, travel times, and other detailed information about transport of constituents in the aquifer were unavailable; however, this information will be needed to create a model with greater spatial resolution and with the capability to predict the impacts of spills and other point sources of pollution. Dye tracing studies are a common method used to develop this information.

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Appendix A
FORTRAN Source Code and User's Guide

```
* Source Code for Barton Springs Groundwater Model
* last modified 6/12/96
* variables:
*    cflow1=onion creek at 1826 (cfs)
*    cflow2=bear creek at 1826 (cfs) (vol doubled in program to account for little bear)
*    cflow3=slaughter at 1826
*    cflow4=williamson at 290
*    cflow5=barton creek at Lost Creek Blvd (cfs)
*    crchg1=onion creek recharge (cfs)
*    crchg2=bear plus little bear recharge (cfs)
*    crchg3=slaughter recharge (cfs)
*    crchg4=williamson recharge (cfs)
*    crchg5=barton creek recharge (cfs)
*    vtank=volume of each tank (cf)
*    atank(i)=effective area of each tank (ft2), 1=onion, 2=bear, 3=slaughter,
*              4=williamson, 5=lower barton, 6=mid barton, 7=upper barton
*    btank(i)=elevation of base of tank above MSL (ft), 1=onion, 2=bear, 3=slaughter,
*              4=williamson, 5=barton,
*    htank(i)=water level in each tank above MSL, i=as above
*    rpipe(i)=flow resistance coefficient(KA/dL), 1=lower onion/bear, 2=bear/slaughter,
*              3=slaughter/williamson, 4=williamson/barton, 5=upper onion/bear
*    btank=elevation of base of tank above MSL (ft)
*    htank=water level in each tank above MSL
*    rpipe=pipe resistance coefficient
*    drchg=average daily infiltration (ft3/ft2)
*    pump(1,5)=average daily pumping in each tank (ft^3)
*    cqual(1,5)=daily average conc in each creek
*    tqual(1,5) = initial concentration in each tank
*    tmass(1,5) = mass of constituent in each tank
*    mrech(1,5) = mass of constituent in creek recharge/day
*    qdrech(1,7)= conc of constituent in diffuse recharge
*    mdrech(1,7)= mass of constituent in diffuse recharge
*    mpump(1,5) = mass removed by pumping
*    vpipe = velocity in each pipe segment (ft/d)
*    plngth(1,7) = distance between tanks
*    ldisp = aL longitudinal dispersivity
*       aname=name of parameter file
*       nday=length of simulation (d)
*       hname=name of output file for water levels
*       iname=name of daily creek flow file
*       pname=name of daily pumping volume file
*       oname=name of spring discharge output file
*       qname=name of file containing creek concentrations (mg/L)
*       cname=name of output file containing cell concentrations (mg/L)
*
```

```
* declare variables
*
      integer i, nday, j
      real cflow(1:5), crchg(1:5), vtank(1:5),
     +atank(1:7), btank(1:5), htank(1:5),
     +rpipe(1:5), fpipe(1:5),bsflow, drchg, sarea(1:5),
     +pump(1:5),cqual(1:5), tqual(1:5), cdis, mrech(1:5),
     +qdrech(1:5), mdrech(1:5), mpump(1:5),plngth(1:4),
     +mcreek,msprng, ldisp, mtank(1:5), mpipe(1:4)
      character*20 oname, aname, hname, pname, onionname, cname,
     +  bearname, slaughtername, williamname,bartonname
      atank(1)=12700e3
      atank(2)=2326e3
      atank(3)=1434e3
      atank(4)=1223e3
      atank(5)=31207e3
      atank(6)=80000e3
      atank(7)=400000e3
      btank(1)=250.0
      btank(2)=250.0
      btank(3)=250.0
      btank(4)=200.0
      btank(5)=350.0
      sarea(1)=780e6
      sarea(2)=780e6
      sarea(3)=139e6
      sarea(4)=167e6
      sarea(5)=167e6
      rpipe(1)=0.0010
      rpipe(2)=0.0032
      rpipe(3)=0.0028
      rpipe(4)=0.0100
      rpipe(5)=0.070
      plngth(1) = 23760.0
      plngth(2) = 23760.0
      plngth(3) = 23760.0
      plngth(4) = 18480.0
*
* read parameter file
*
      print*, 'enter name of aquifer parameter file'
      read '(A)',aname
      open (unit = 6, file = aname, status = 'old')
      read (6, *) nday
      read (6,5) onionname
```

```
      read (6,5) bearname
      read (6,5) slaughtername
      read (6,5) williamname
      read (6,5) bartonname
      read (6,5) pname
      read (6,5) oname
      read (6,5) hname
      read (6,5) cname
      read (6, *) (vtank(i), i=1,5)
      read (6, *) (tqual(i), i=1,5)
      read (6, *) drchg
      read (6, *) (qdrech(i), i=1,5)
      read (6, *) ldisp
5     Format (A)
*
* open input and output files
*
      open (unit = 7, file = onionname, status = 'old')
      open (unit = 8, file = bearname, status = 'old')
      open (unit = 9, file = slaughtername, status = 'old')
      open (unit = 10, file = williamname, status = 'old')
      open (unit = 11, file = bartonname, status = 'old')
      open (unit = 13, file = oname, status = 'new')
      open (unit = 14, file = hname, status = 'new')
      open (unit = 15, file = pname, status = 'old')
      open (unit = 16, file = cname, status = 'new')
*
*     calculate initial mass in each tank (kg)
*
      do 8 j=1,5
      mtank(j)=tqual(j)*vtank(j)*28.32e-6
8     continue
*
*     read daily input values
*
      do 195  i = 1, nday
10      read (7, *) cflow(1), cqual(1)
        read (8, *) cflow(2), cqual(2)
        read (9, *) cflow(3), cqual(3)
        read (10, *) cflow(4), cqual(4)
        read (11, *) cflow(5), cqual(5)
        read (15,*) (pump(j), j=1,5)
*
* calculate onion creek recharge, max 120 cfs
*
```

```
      if (cflow(1) .lt. 120.0) then
            crchg(1) = cflow(1)
      else
            crchg(1) = 120
      endif
*
* calculate bear creek plus little bear recharge
*
      if (cflow(2) .lt. 33.0) then
            crchg(2) = 2*cflow(2)
      else
            crchg(2) = 66.0
      endif
*
* calculate slaughter creek recharge
*
      if (cflow(3) .lt. 52.0) then
            crchg(3) = cflow(3)
      else
            crchg(3) = 52.0
      endif
*
* calculate williamson creek recharge
*
      if (cflow(4) .lt. 13.0) then
            crchg(4) = cflow(4)
      else
            crchg(4) = 13.0
      endif
*
* calculate barton creek recharge
*
      if (cflow(5) .LT. 30.0) then
         crchg(5) = cflow(5)
      else
         if(cflow(5) .LT. 1000.0) then
            crchg(5) = -(1e-8)*cflow(5)**3 + 0.0001*cflow(5)**2 +
     +        0.1349*cflow(5)+25.1
         else
             crchg(5)=250.0
         endif
      endif
*
* calculate mass of constituent in creek recharge/d
*
```

```
      do 15, j=1,5
      mrech(j) = 86400.0*crchg(j)*cqual(j)*28.32e-6
15      continue
*
* calculate mass of constituent in diffuse recharge/d
*
      do 17, j=1,5
      mdrech(j) = sarea(j)*drchg*qdrech(j)*28.32e-6
17      continue
*
* calculate mass in tank lost to pumping
*
      do 18, j=1,5
      mpump(j) = pump(j)*mtank(j)/vtank(j)
18      continue
*
* calculate water levels in each tank except barton
*
      do 20 j=1,4
      htank(j) = vtank(j)/atank(j) + btank(j)
20      continue
*
* calculate barton tank height (3 zones, porosity increasing upward)
*
        if (vtank(5) .LT. 2.661e9) then
            htank(5) = (vtank(5))/atank(5) + btank(5)
            else
              if(vtank(5) .LT. 2.824e9) then
                  htank(5) = (vtank(5)-2.661e9)/atank(6) + 435.26
                 else
                    htank(5)=(vtank(5)-2.824e9)/atank(7) + 437.3
              endif
        endif
*
* calculate flow in each of 4 pipe segments
*
      do 30 j=1,4
      fpipe(j) = rpipe(j)*(htank(j)-btank(j))*(htank(j)-htank(j+1))
30      continue
      if (htank(1) .GT. 600.0) then
          fpipe(1) = rpipe(1)*(600.0-btank(1))*(htank(1)-htank(2))+
     +          rpipe(5)*(htank(1)-600.0)*(htank(1)-htank(2))
      else
          fpipe(1)=fpipe(1)
      endif
```

```
*
* calculate mass transferred through pipes (advection+dispersion)
*
      do 35 j=1,4
      if (fpipe(j) .GT. 0.0) then
         mpipe(j)= 86400.0*((fpipe(j)*mtank(j)/vtank(j))+ ldisp*
     +        fpipe(j)*((mtank(j)/vtank(j)-mtank(j+1)/vtank(j+1))/
     +        plngth(j)))
      else
         mpipe(j)= 86400.0*((fpipe(j)*mtank(j+1)/vtank(j+1))+ ldisp*
     +        fpipe(j)*((mtank(j+1)/vtank(j+1)-mtank(j)/vtank(j))/
     +        plngth(j)))
      endif
35    continue
*
* calculate flow at barton springs (valid for 20<flow<120 cfs)
*
      bsflow = 42.88*((htank(5)-432.82)**0.6279)
*
* calculate mass discharged at barton springs/d
*
      msprng = 86400.0*bsflow*mtank(5)/vtank(5)
*
*  calculate discharge to creek during high water levels
*
      if(bsflow .GT. 80.0) then
         cdis = (bsflow - 80.0)*0.6
      else
         cdis = 0
      endif
*
* calculate mass discharged to creek during high water levels/d
*
      mcreek = 86400.0*cdis*mtank(5)/vtank(5)
*
* calculate tank volumes
*
      vtank(1)=vtank(1)+86400.0*(crchg(1)-fpipe(1))+
     + sarea(1)*drchg - pump(1)
      vtank(2)= vtank(2) + 86400.0*(crchg(2)-fpipe(2)+fpipe(1))
     + + sarea(2)*drchg - pump(2)
      vtank(3) = vtank(3) + 86400.0*(crchg(3) + fpipe(2)
     +  - fpipe(3)) + sarea(3)*drchg - pump(3)
      vtank(4) = vtank(4) + 86400.0*(crchg(4) + fpipe(3)
     +  - fpipe(4)) + sarea(4)*drchg - pump(4)
```

```
      vtank(5) = vtank(5) + 86400.0*(crchg(5)+fpipe(4)
     +  - bsflow -cdis) + sarea(5)*drchg - pump(5)

*
* calculate mass in each tank
*
      mtank(1)=mtank(1)-mpipe(1)-mpump(1)+mdrech(1)+mrech(1)
      mtank(2)=mtank(2)+mpipe(1)-mpipe(2)-mpump(2)+mdrech(2)+mrech(2)
      mtank(3)=mtank(3)+mpipe(2)-mpipe(3)-mpump(3)+mdrech(3)+mrech(3)
      mtank(4)=mtank(4)+mpipe(3)-mpipe(4)-mpump(4)+mdrech(4)+mrech(4)
      mtank(5)=mtank(5)+mpipe(4)-msprng+mdrech(5)+mrech(5)-mcreek-
     +   mpump(5)
*
* calculate concentration in each tank (mg/L)
*
      do 180 j=1,5
      tqual(j)=mtank(j)/(vtank(j)*28.32e-6)
180   continue
*
* print barton springs flow and water levels and concentration to a file
*
190   Format (5F5.0)
      write(13,*) bsflow
      write (14,190) (htank(j), j = 1,5)
      write (16, 194) (tqual(j), j=1,5)
194   Format (5F8.3)
195   end do
200   end
```

User's Guide for the CRWR Barton Springs Groundwater Model

Required Model Inputs

This groundwater model has been developed to predict water levels, spring discharge, and water quality for the Barton Springs portion of the Edwards aquifer. The model calculates recharge and aquifer state from daily flow rates, water quality in the five main creeks, pumping volumes for each of the five cells, and daily infiltration rate. Seven input files are required for use of the model: a simulation parameter file, a file of daily flow rates and quality for each of the five creeks, and a file containing average daily pumping volumes.

Simulation Parameter File

The simulation parameter file is a text file which specifies the names of input data files and output files. It also specifies the length of the simulation and the water volume and quality of each of the five cells at the start of the run. In general, modifications of the input file will be limited to changing the length of the simulation or the input and output file names. The file has the following structure:

Length of simulation (integer value in days)
Name of file containing Onion Creek flow and quality data (character)
Name of file containing Bear Creek flow and quality data (character)
Name of file containing Slaughter Creek flow and quality data (character)
Name of file containing Williamson Creek flow and quality data (character)
Name of file containing Barton Creek flow and quality data (character)
Name of file containing pumping data (character)
Name of file for output of Barton Springs flow prediction (character)
Name of file for output of water level elevations (character)
Name of file for output of concentrations of the five cells (character)
Initial water volume of each cell (5 real values, ft^3)
Onion, Bear, Slaughter, Williamson, Barton
Initial constituent concentration in each cell (5 real values, mg/L)
Rate of diffuse infiltration (real, ft/d)
Concentration in diffuse recharge for each cell (5 real values, mg/L)
Longitudinal dispersivity (real, ft)

A simulation parameter file (a.txt), data files for each of the creeks (onion.txt, bear.txt, slauter.txt, will.txt, barton.txt), and pumping file (pump.txt) is included with the program. The parameter file calls for a simulation lasting for 5905 days; however, there is no inherent maximum length of the simulation. The associated data files contain the information describing creek flow and pumping for the period 8/1/79 through 9/30/95. The initial water volumes in this file will produce the water levels measured in the aquifer on approximately 8/1/79. The names of the output files for spring flow, water levels, and aquifer quality are arbitrary character strings. All file names are restricted to a length of 20 characters. A sample parameter file is shown below.

```
5905
onion.txt
bear.txt
slauter.txt
will.txt
barton.txt
pump.txt
out.txt
hgt.txt
conc.txt
2857E6 581E6 358E6 306E6 2726E6
1.5 2.0 2.0 2.0 1.6
0.00046
6.56 6.56 6.56 6.56 6.56
0.0
```

Creek Data File

The creek data file contains daily average flow rate (ft^3/s) and concentration (mg/L) for one constituent. This is a free format text file containing data in two columns. Each row contains the values for a single day of creek flow. The flow rates should be those either expected or measured at the USGS gauging stations on each creek located immediately upstream of the recharge zone. The location of the stations on each creek is shown in Table A-1. The values shown in the example file in Table A-2 for Onion Creek are tab separated.

Table A-1 Location of Creek Flow Measurements

Creek	Station Description	USGS ID Number
Onion	FM 150 near Driftwood	08158700
Bear	FM 1826 near Driftwood	08158810
Slaughter	FM 1826	08158840
Williamson	Hwy 290 at Oak Hill	08158920
Barton	Lost Creek Boulevard	08155240

Table A-2 Sample Creek Input File

```
13      0.55
13      0.55
91      0.67
88      0.55
225     0.67
115     0.55
101     0.55
87      0.55
77      0.55
82      0.55
74      0.55
255     0.67
145     0.55
124     0.55
114     0.55
107     0.55
101     0.55
```

Pumping Volume File

This file contains the daily volume (ft^3) pumped from each of the five cells. It is a text file with five columns, and each row contains the values from a single day. The values must be real and are in the following order: Onion, Bear, Slaughter, Williamson, Barton. Since only monthly estimates of pumping volumes were available, average daily volumes were calculated for each month and used in the attached file *pump.txt*. The most complete pumping data available was from 1994, so those values were used for each year of the example simulation. A portion of that file is shown in Table A-3.

Table A-3. Example of Pumping Volume File (pump.txt)

3.16E+05	3.05E+05	2.00E+04	2.67E+04	2.26E+04
3.16E+05	3.05E+05	2.00E+04	2.67E+04	2.26E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04
2.51E+05	2.10E+05	1.52E+04	1.41E+04	1.27E+04

Word of Warning

This model was developed and calibrated using historical data collected between 1979 and 1995. During this period, the discharge at Barton Springs varied between 14 and 130 cfs. Use of input data from other periods may result in predicted discharge which is outside of the range the model is known to represent successfully. In such cases, predictions of discharge and associated water levels should be treated qualitatively, since aquifer response at very low and very high water levels is unknown.

Appendix B
Comparison of Predicted with Observed Water Levels for Aquifer Cells

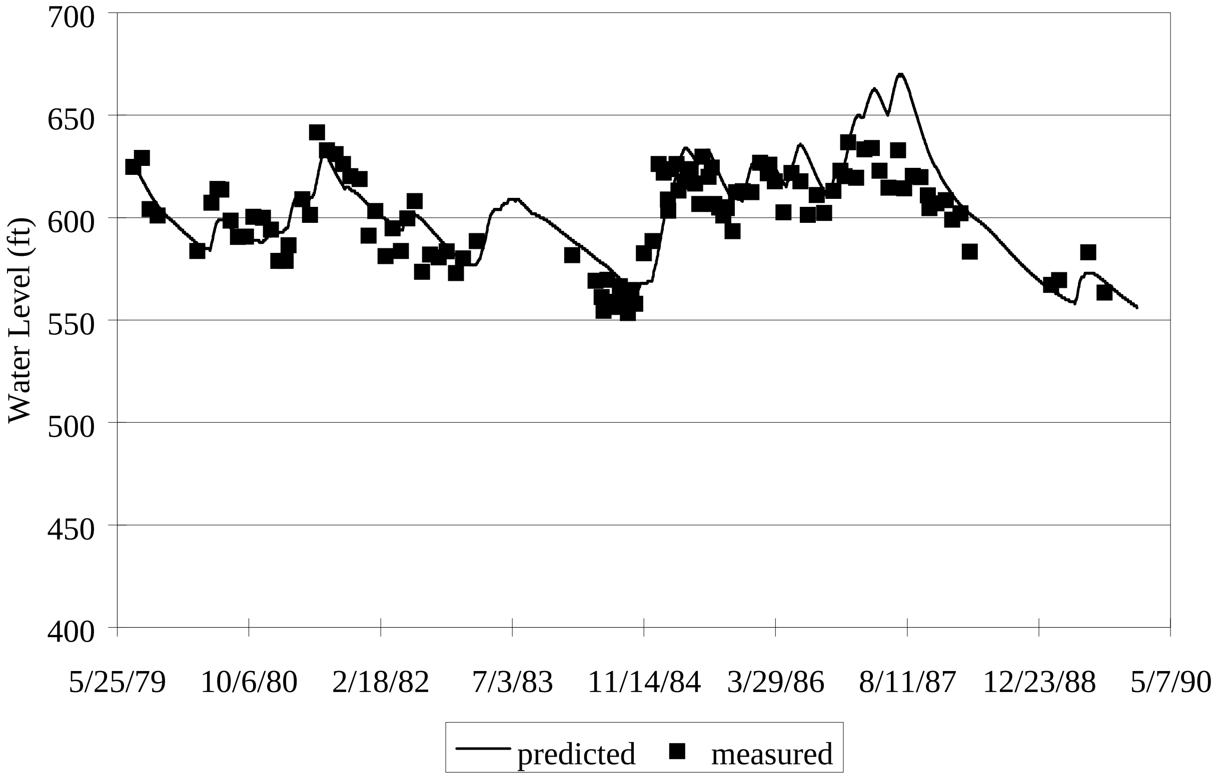

Figure B-1 Comparison of Measured and Predicted Level for the Onion Cell

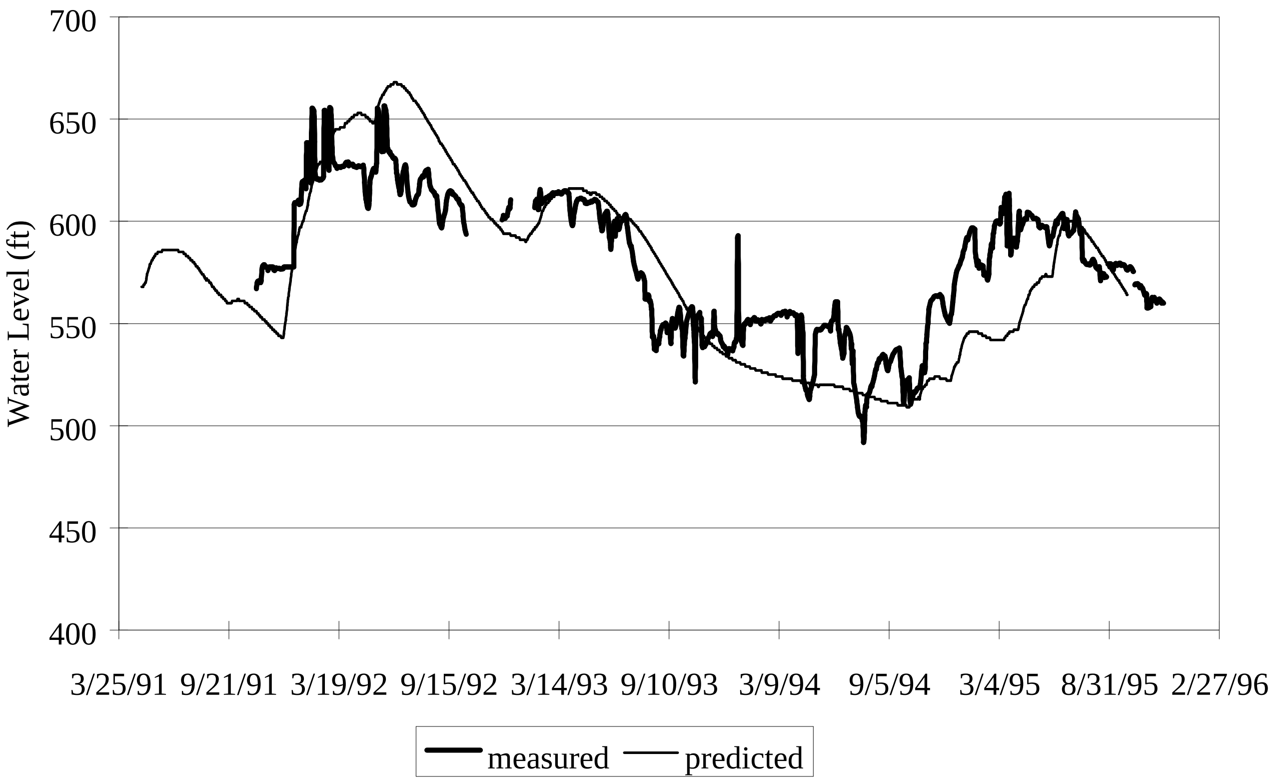

Figure B-2 Comparison of Measured and Predicted Level for the Bear Cell

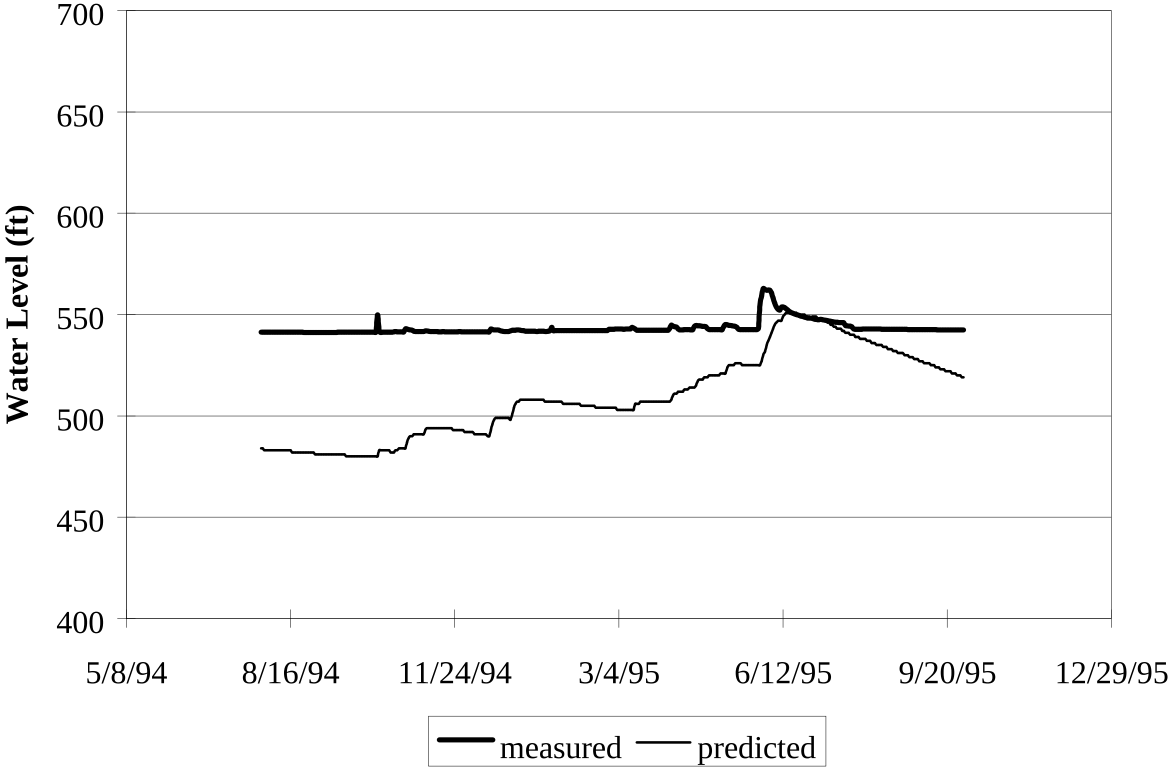

Figure B-3 Comparison of Predicted Slaughter Cell Level with Circle C Well

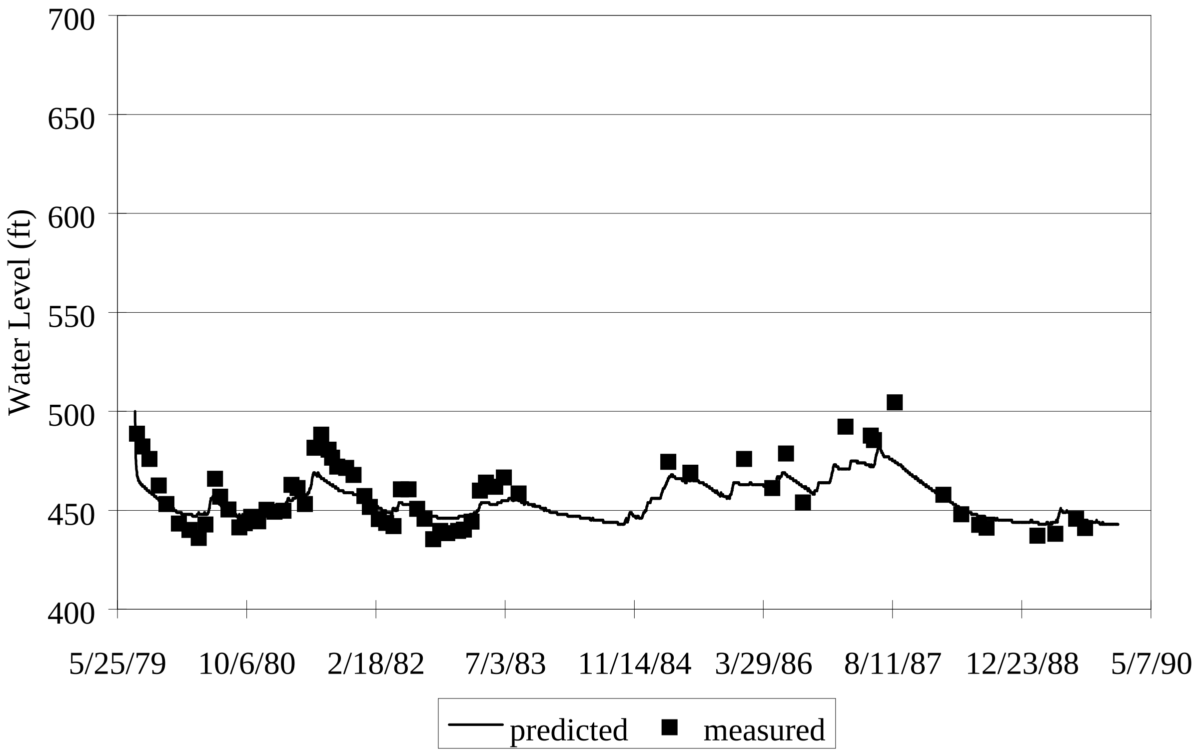

Figure B-4 Comparison of Measured and Predicted Water Levels in the Williamson Cell

Appendix C
Effect of Development on Aquifer Level and Water Quality

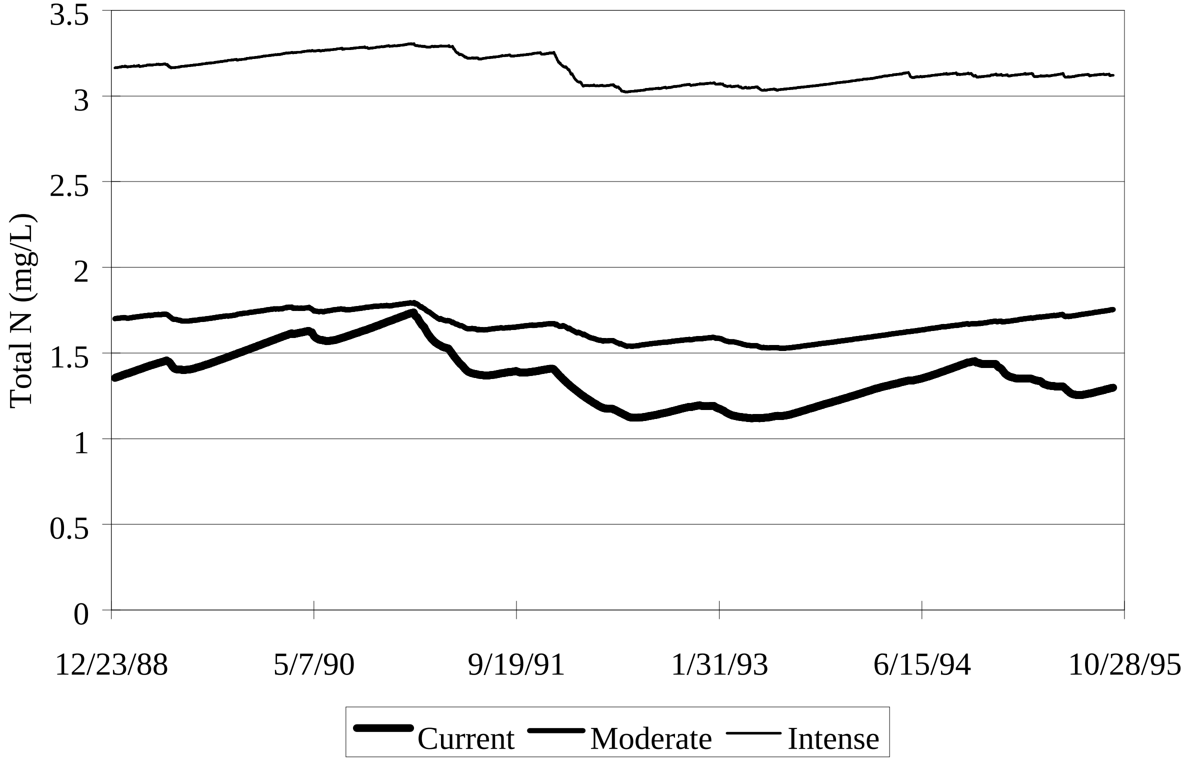

Figure C-1 Effect of Development on Onion Cell Quality

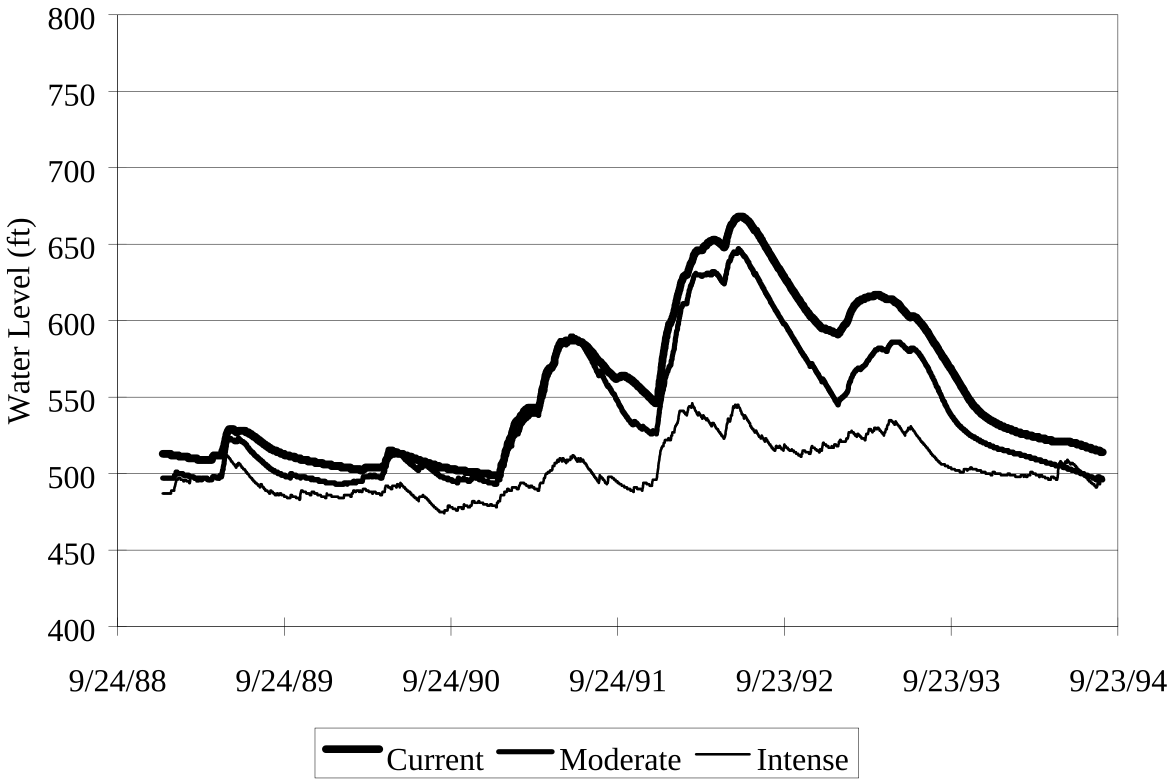

Figure C-2 Effect of Development on Bear Cell Water Level

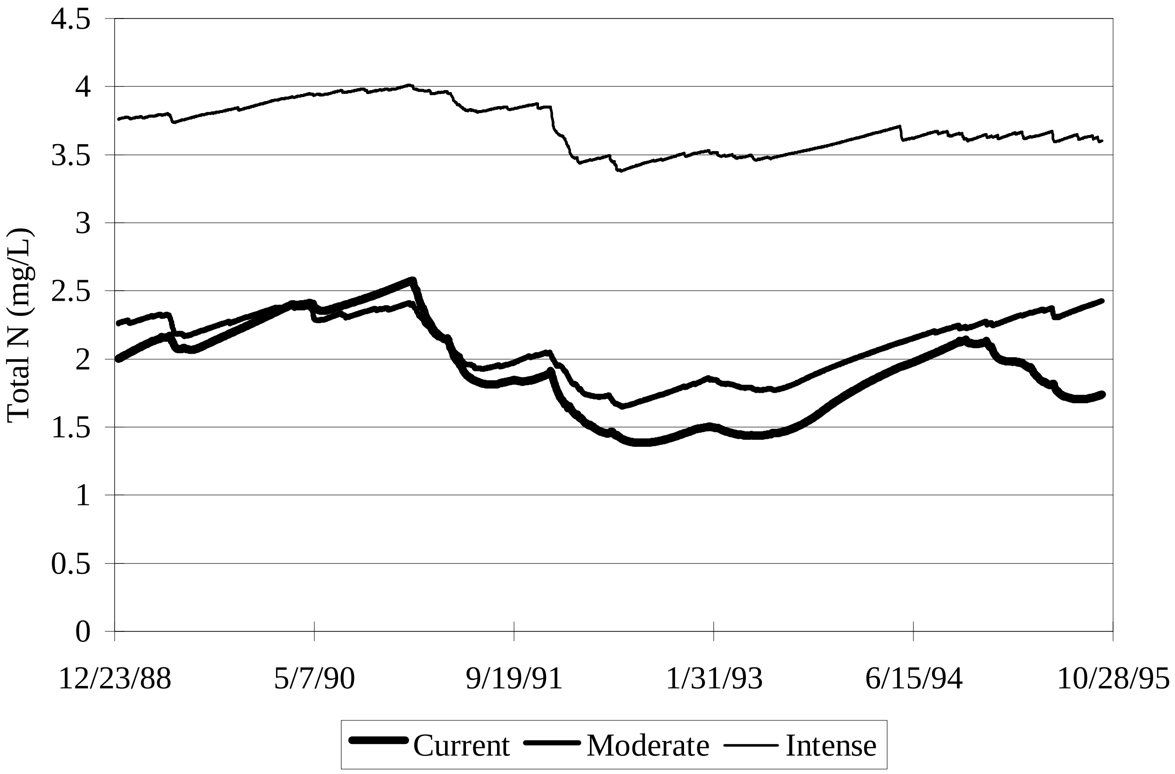

Figure C-3 Effect of Development on Bear Cell Quality

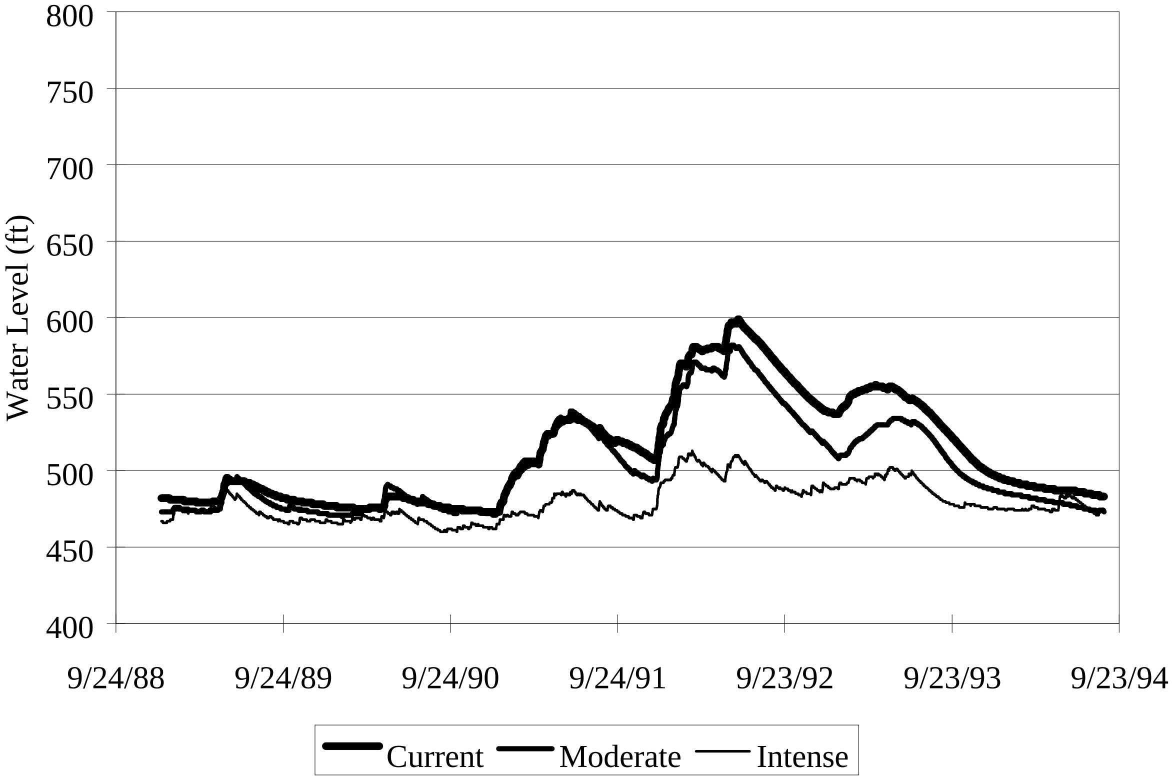

Figure C-4 Effect of Development on Slaughter Cell Water Level

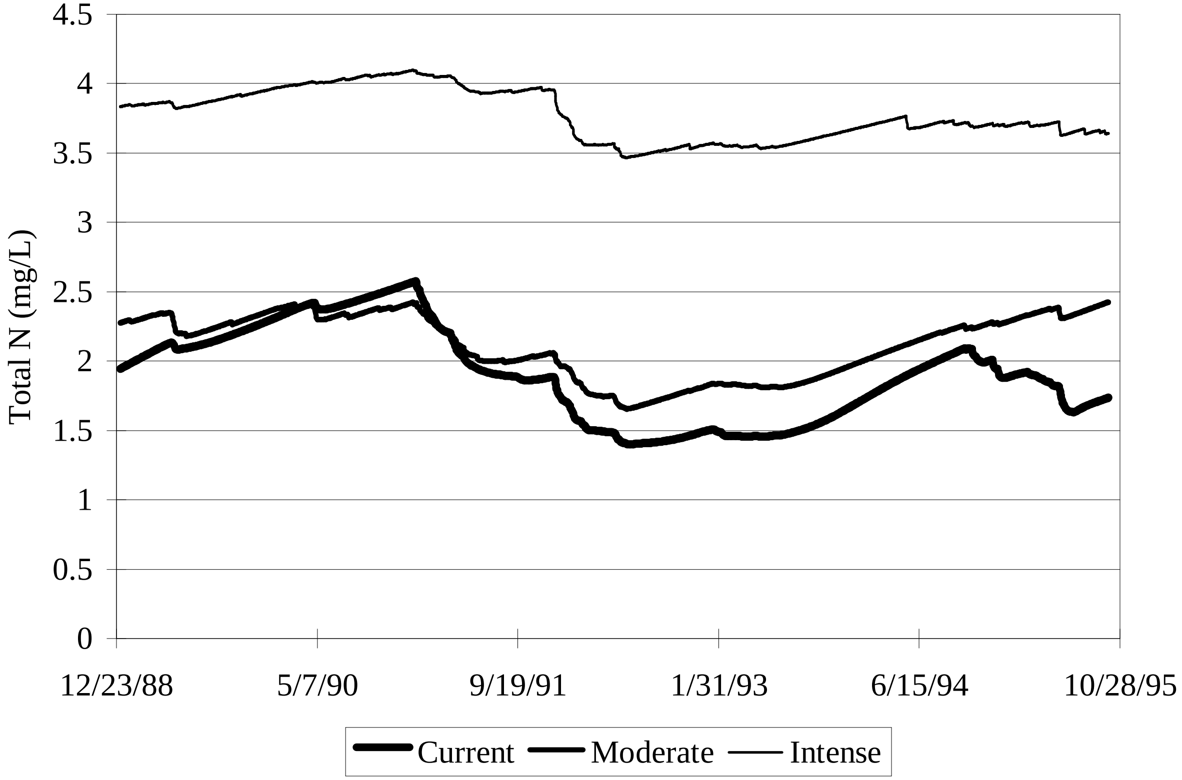

Figure C-5 Effect of Development on Slaughter Cell Quality

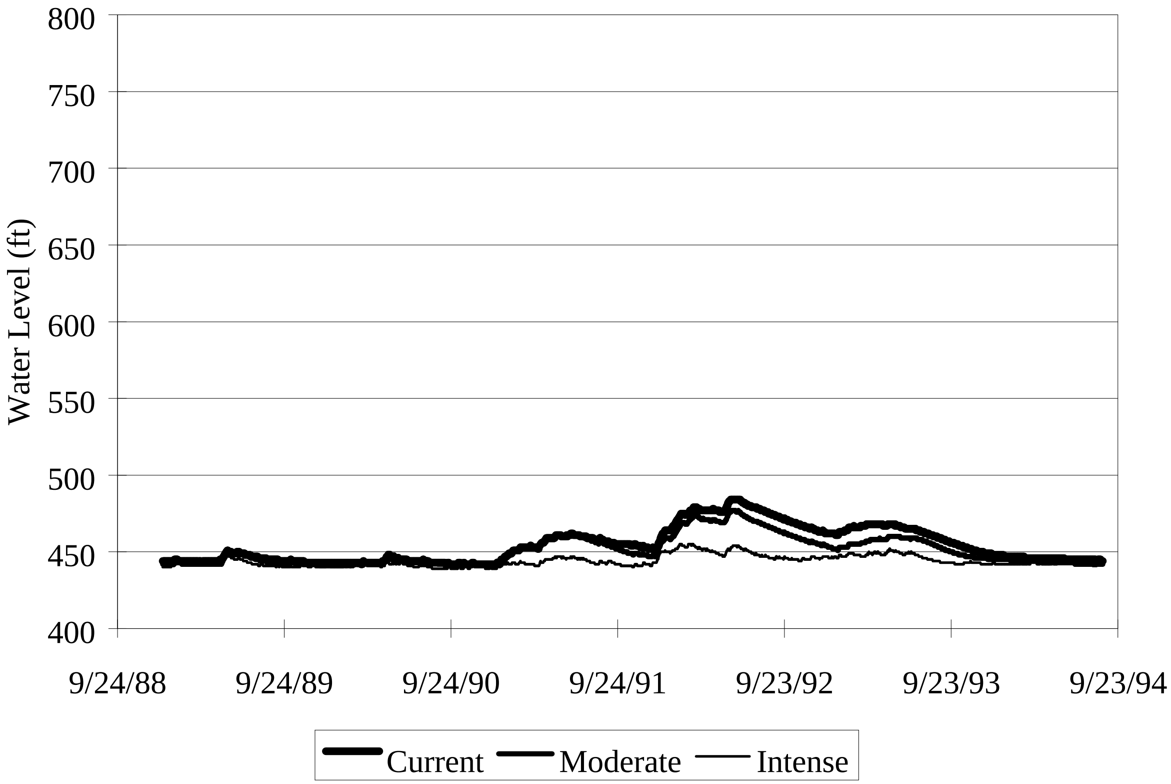

Figure C-6 Effect of Development on Williamson Cell Water Level

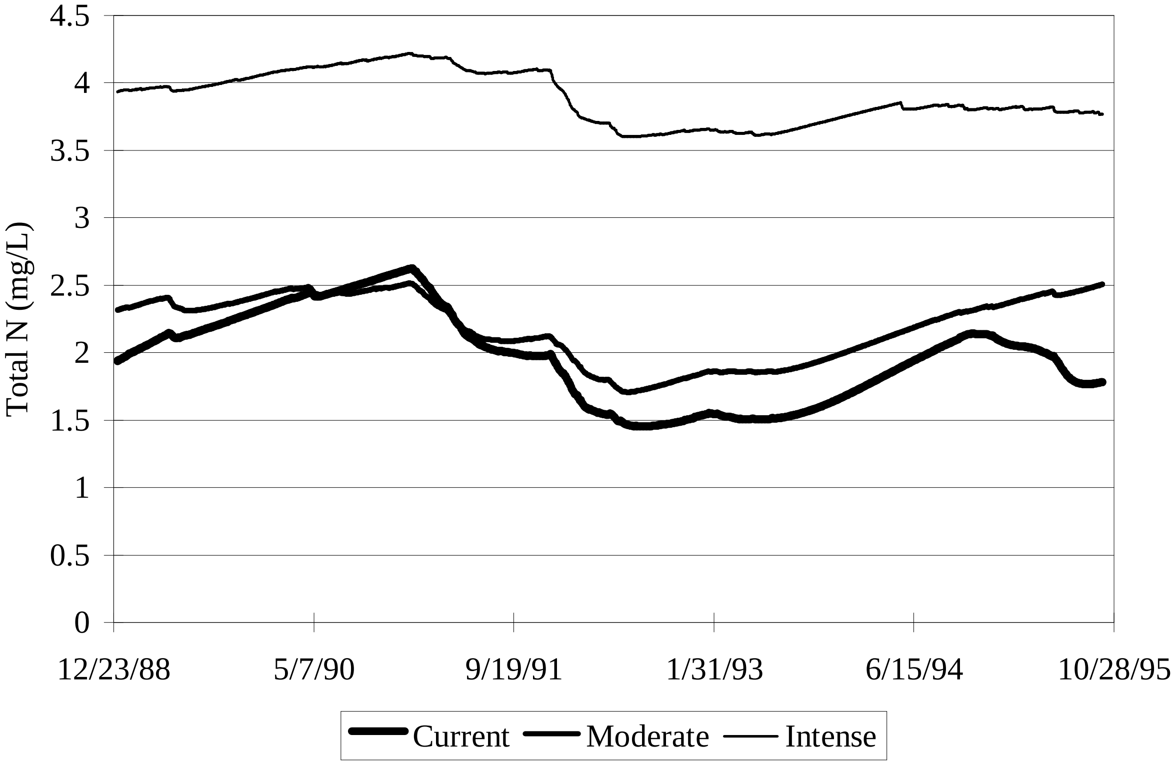

Figure C-7 Effect of Development on Williamson Cell Quality