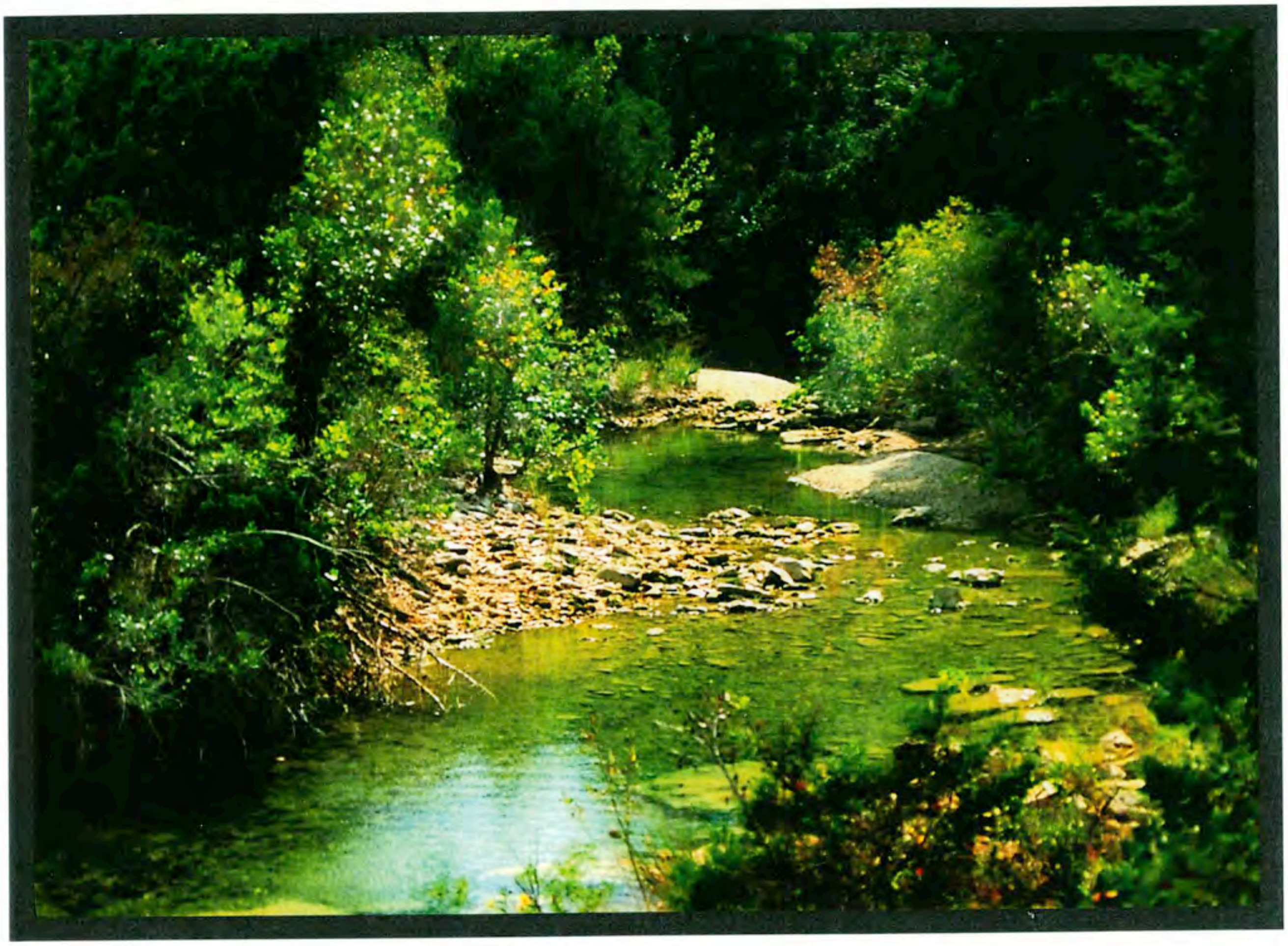
THE BARTON CREEK REPORT



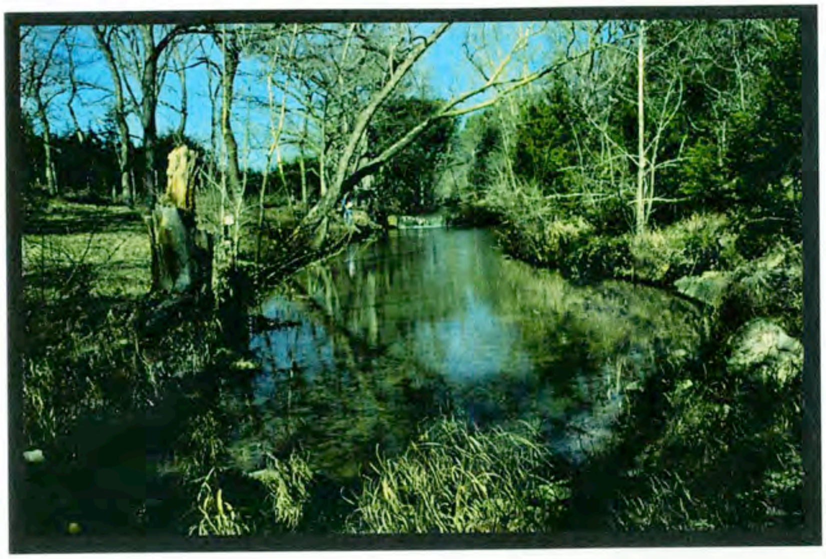
City of Austin
Drainage Utility Department
Environmental Resources Management Division

Water Quality Report Series
COA-ERM/ 1997

April 22, 1997

FINAL

BARTON CREEK POOL SITES



Pool 1

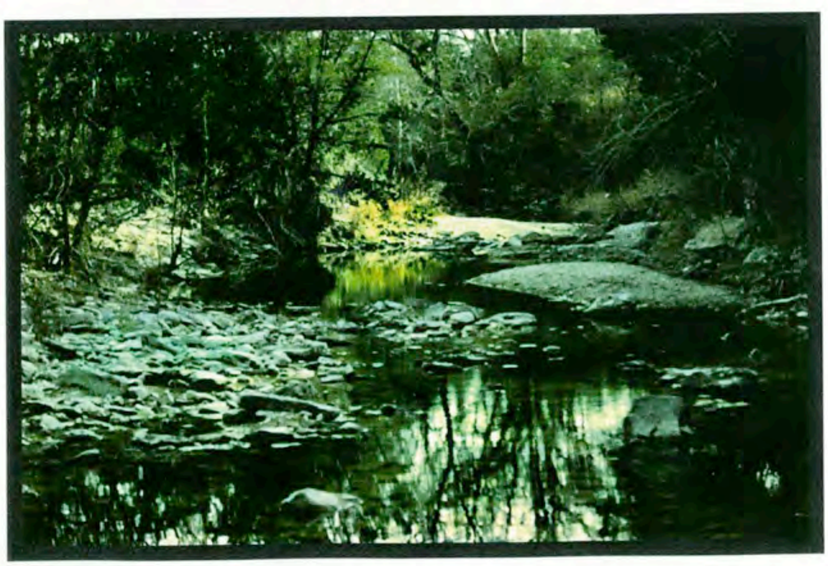
Pool 2

Pool 3

BARTON CREEK POOL SITES cont'd

Pool 4

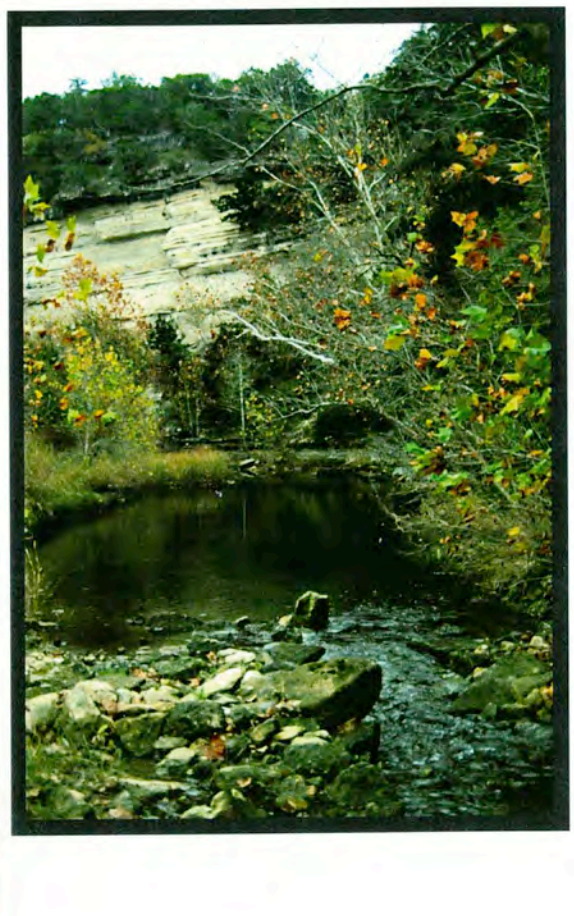
Pool 5



Pool 6

BARTON CREEK POOL SITES cont'd

Pool 7



Pool 8

Pool 9

Appendix B - Project Photos

Photo 1A

Surface waters recharge the Edwards Aquifer in a swirling vortex created by a solution cavity in the creekbed.

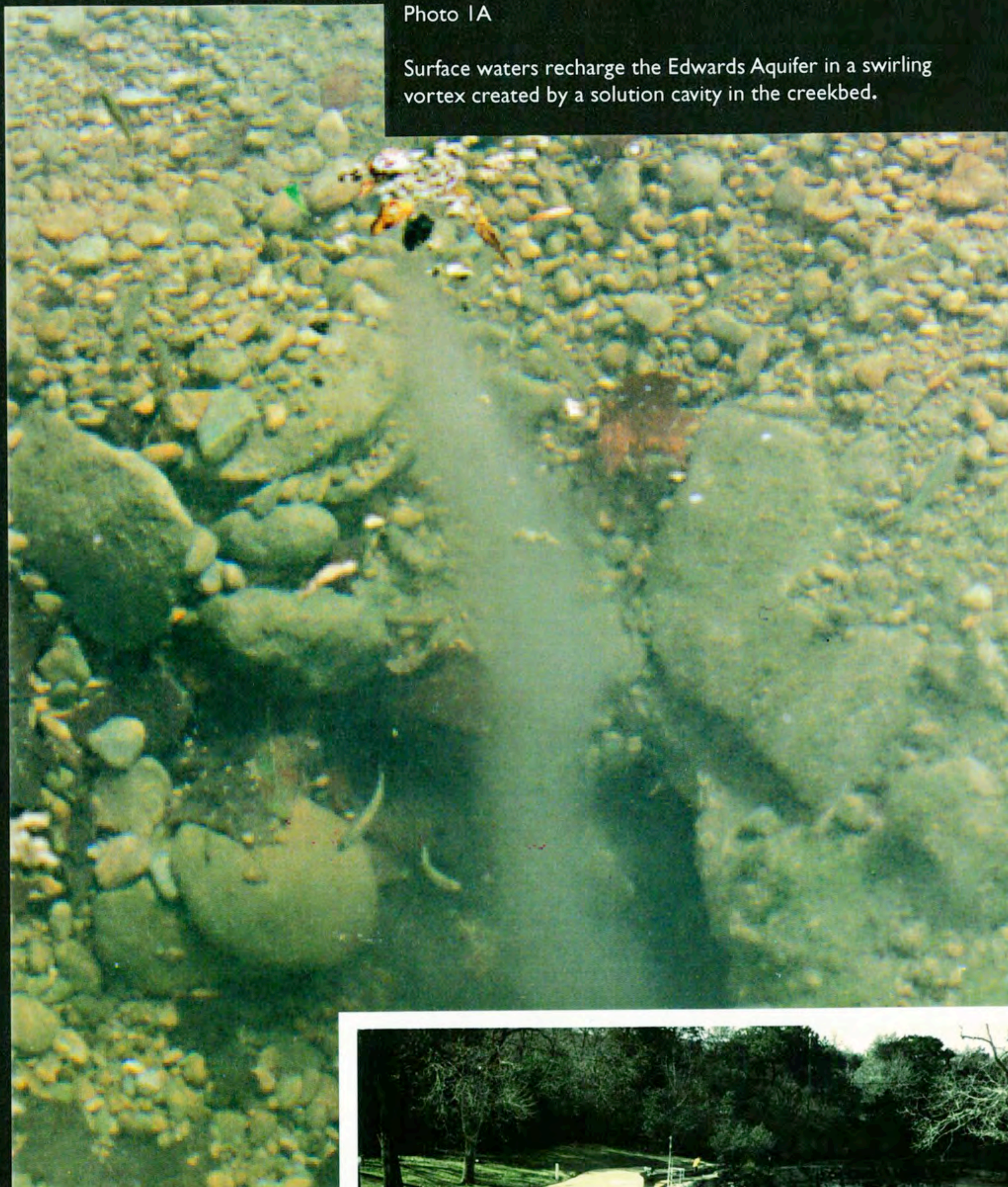


Photo 1B

The culmination of the water's journey through the aquifer is Barton Springs, the major discharge point for the Barton Springs segment of the Edwards Aquifer.

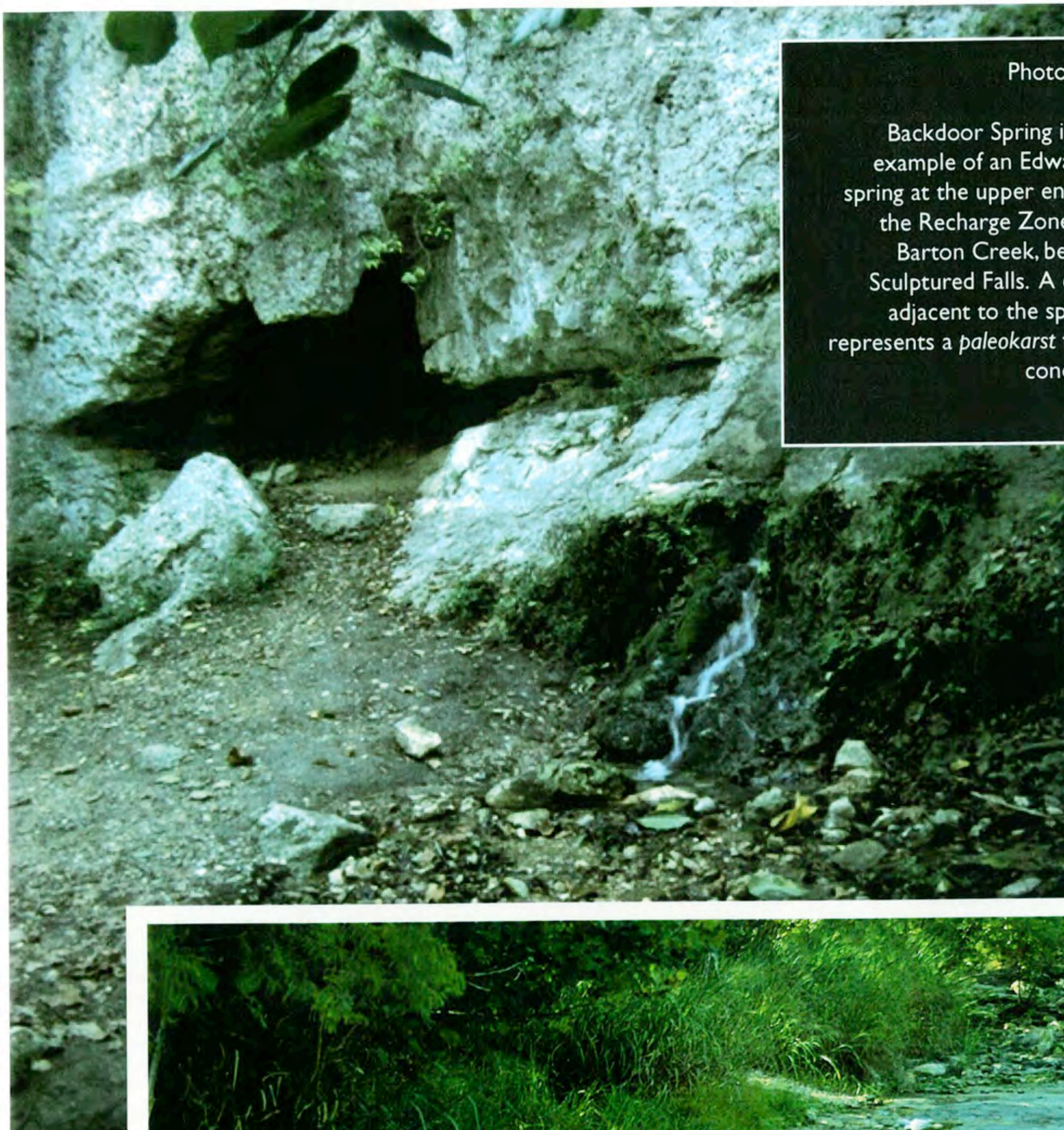


Photo 2A

Backdoor Spring is an example of an Edwards spring at the upper end of the Recharge Zone on Barton Creek, below Sculptured Falls. A cave adjacent to the spring represents a *paleokarst* flow conduit.

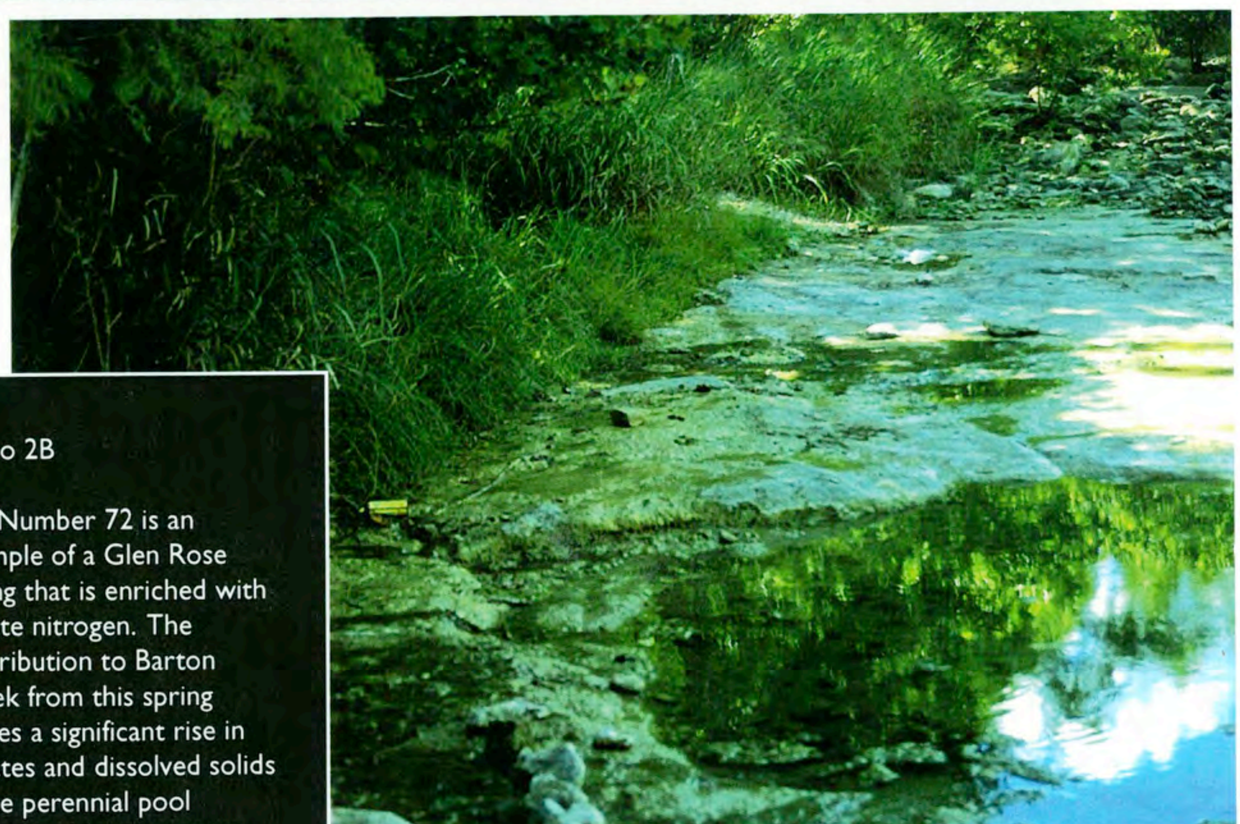


Photo 2B

Site Number 72 is an example of a Glen Rose spring that is enriched with nitrate nitrogen. The contribution to Barton Creek from this spring causes a significant rise in nitrates and dissolved solids in the perennial pool immediately downstream.

Photo 3A

Residential development is the most common type of new construction in the Barton Creek watershed. This study has shown significant differences in water quality between residentially-developed tributaries and rural tributaries.

Photo 3B

Significant differences in water quality have been shown between tributaries on golf courses and rural tributaries.

Photo 4A

Tributaries and springs on undeveloped or rural lands have been shown to have the best water quality, with the exception of bacteria concentrations in some areas.

Photo 4B

Fecal coliform bacteria concentrations are highest in some areas along Barton Creek where cattle are raised; however, these bacteria concentrations are relatively low when compared to concentrations from fully-developed urban watersheds.

Photo 5A

Most of Barton Creek's mainstem runs clean and clear.

Photo 5B & C

High turbidity may result from fine sediments deposited in pools downstream of construction projects.

Photo 6A

A diverse community of algae and aquatic macrophytes inhabits pools which have not been impacted by nutrient enrichment.

Photo 6B

"Carpet algae" is ubiquitious in Barton Creek and is a composite of bluegreen algae, diatoms, and sediment.

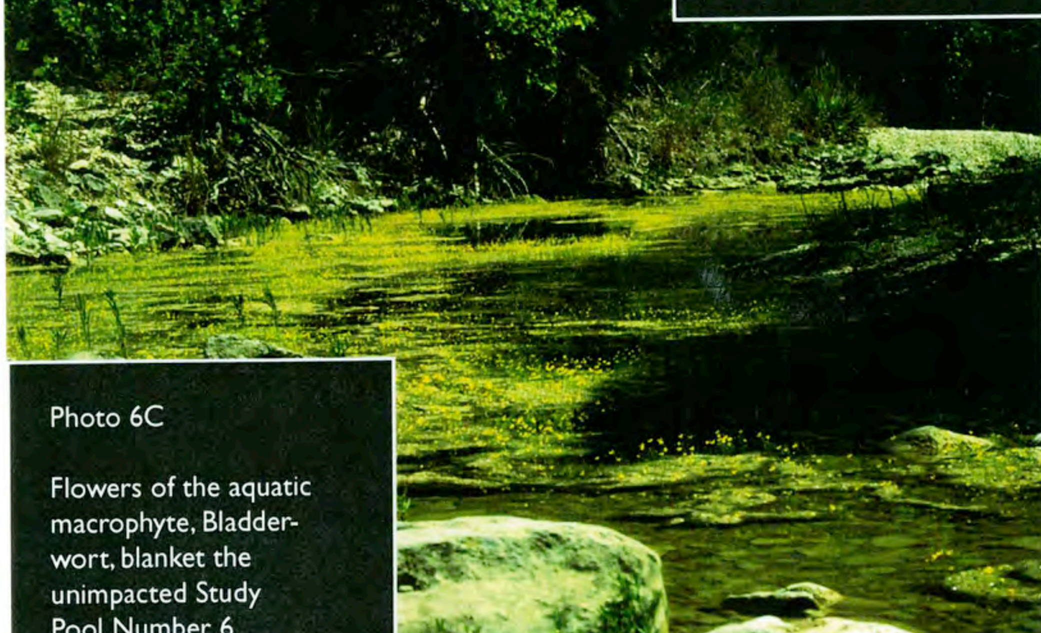


Photo 6C

Flowers of the aquatic macrophyte, Bladderwort, blanket the unimpacted Study Pool Number 6.

Photo 7A

Massive *Cladophora* algae blooms have occurred in reaches of Barton Creek adjacent to golf courses irrigated with treated wastewater effluent.

Photo 7B

Higher nutrient concentrations predicted to result from future urbanization, may result in more frequent blooms of nuisance algae in Barton Creek.

Photo 8A

More filamentous algae is sustained in study pools with elevated nitrates than in unimpacted pools.

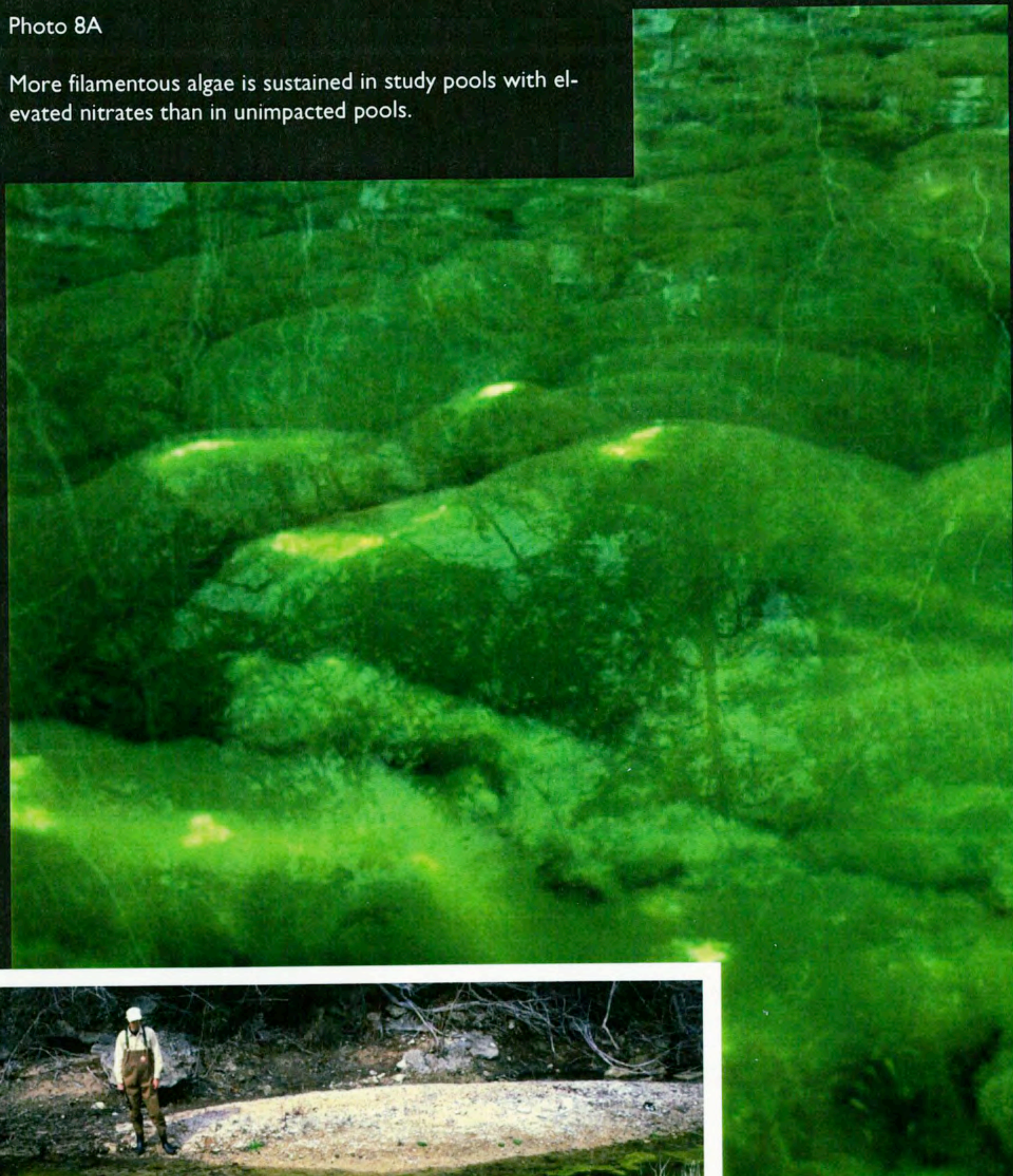
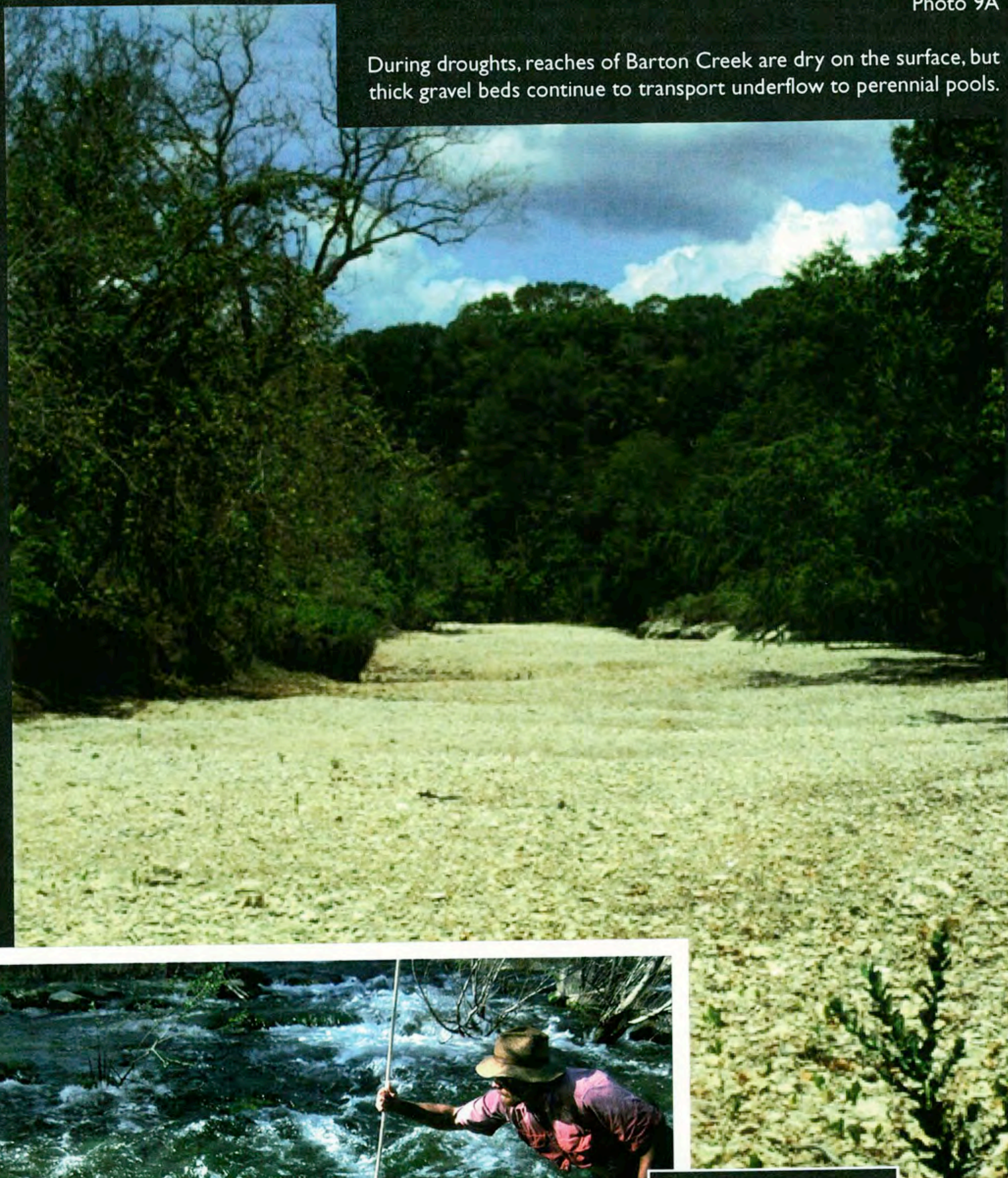


Photo 8B

Spirogyra-type blooms are more ephemeral than *Cladophora* blooms and can occur anywhere along Barton Creek when environmental conditions are favorable.

Photo 9A

During droughts, reaches of Barton Creek are dry on the surface, but thick gravel beds continue to transport underflow to perennial pools.



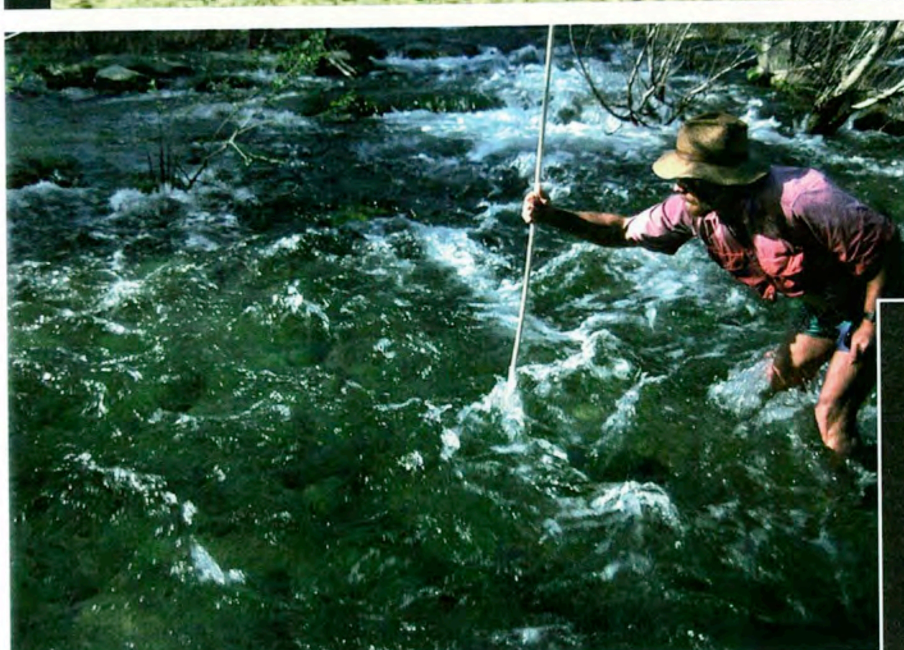


Photo 9B

During high flows, local urban impacts are diminished, resulting in relatively uniform water quality in Barton Creek's mainstem.

Photo 10A

The Barton Springs salamander has become a symbol of the unique, fragile nature of the Barton Creek/Barton Springs system.

Photo 10B

Efforts are underway to estimate variability in the surface population of the salamander and to study the species ecological requirements.

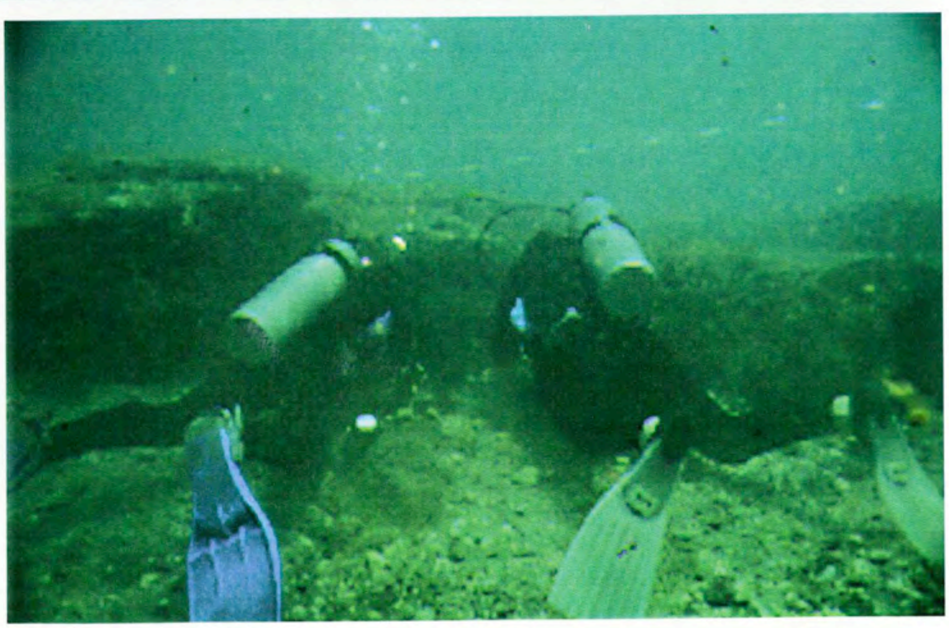


Photo 11A

Further urbanization of the watershed is predicted to increase pool closings because of turbidity. Predicted increases in peak flows may also result in more frequent closings owing to flooding of the pool by Barton Creek.

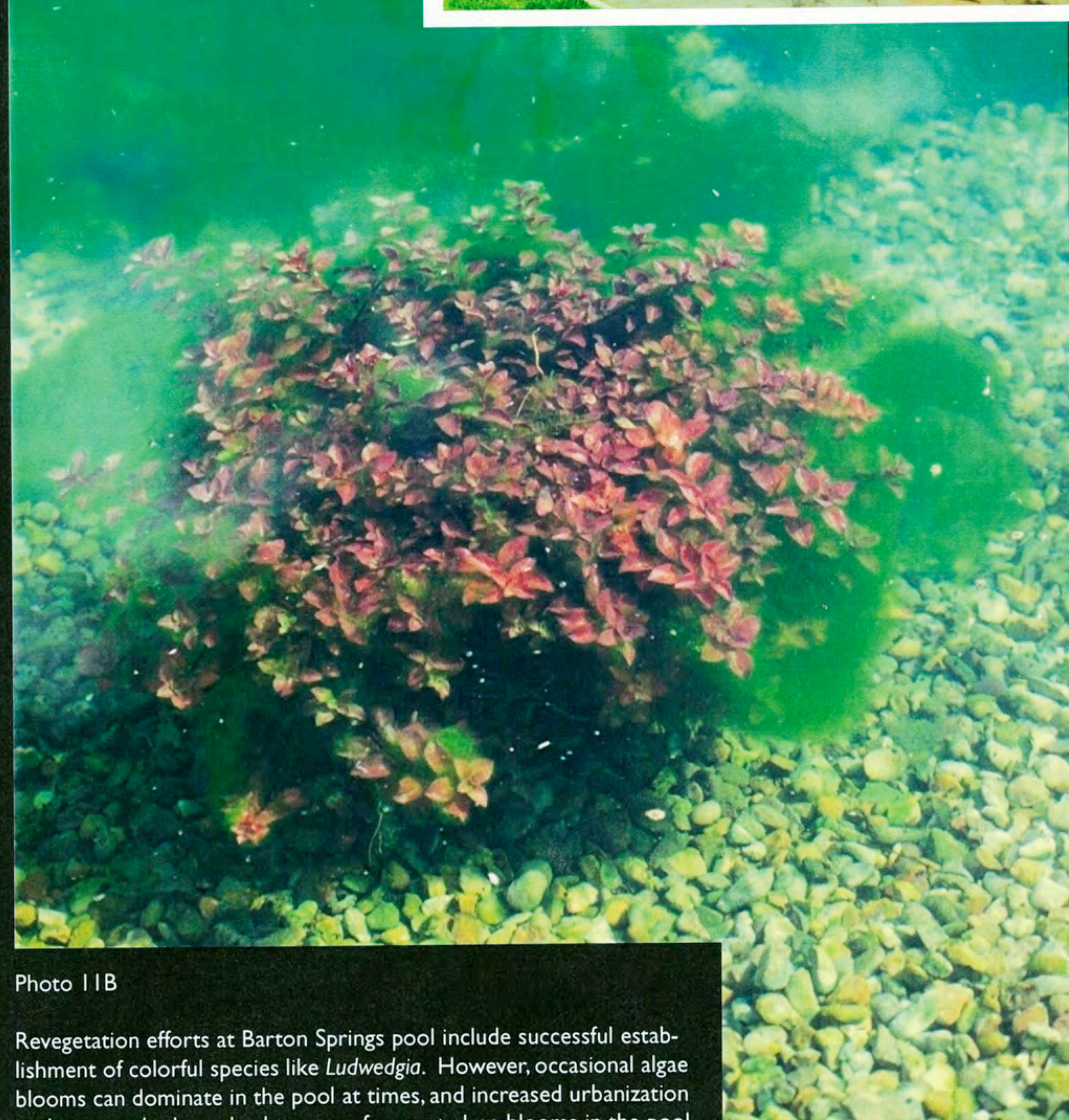


Photo 11B

Revegetation efforts at Barton Springs pool include successful establishment of colorful species like *Ludwedgia*. However, occasional algae blooms can dominate in the pool at times, and increased urbanization in the watershed may lead to more frequent algae blooms in the pool.

THE BARTON CREEK REPORT

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City of Austin

Drainage Utility Department

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THE BARTON CREEK REPORT

EXECUTIVE SUMMARY

Purpose

This report presents the Austin City Council, the Environmental Board, and the community at large a comprehensive account of the water quality investigations completed by the City's Environmental Resources Management (ERM) staff and provides a "state of the creek" report for its most popular natural resource, the Barton Creek/Barton Springs system.

The studies described in this report attempt to diagnose the level of impact on Barton Creek's water quality from urbanization activities such as large scale land developments, wastewater disposal alternatives, golf course and residential landscape maintenance, and cattle ranching. The primary approach in most of the studies is to monitor ground water, surface water, sediments, and biology of Barton Creek and compare urban or developed sites with rural or undeveloped sites. The primary pollution impairments of concern include sedimentation, nutrient enrichment, bacterial contamination, and toxic substance contamination. These constituents are measured directly from the water and sediments, and their impact is measured using various ecological methods assessing the diversity and abundance of aquatic plant and animal communities. Elements of this report include both comprehensive narratives of previously unreleased studies as well as summaries of studies which have recently been released.

Directives

Espey Huston and Associates (EHA) provided a baseline of data on the Barton Creek Watershed in 1979 with their Barton Creek Watershed Study, written for the City's Office of Environmental Resource Management (EHA, 1979). They identified gaps in the ecological information and described studies needed for better understanding of Barton Creek, its protection, and management. EHA stated that the existing data base was not adequate to determine the effects of development. A resolution passed by the Austin City Council on

October 15, 1987 directed the City's Department of Environmental Protection to assist the Environmental Board in a short term review and analysis of existing data on the Barton Creek Watershed. The resulting 1988 City Manager's Barton Creek Policy Definition Report was endorsed by the Environmental Board, and the recommendation for Action Group III-2 was -- "continue to monitor and report upon changes in baseline conditions of land and water resources in the watershed which are attributable to urban development." Such is the essential focus of this report. Although this directive was made in 1988, funding, staff, equipment, and monitoring plans were not solidified until 1990, and monitoring for several study elements did not begin until 1992 or 1993. The following projects are documented in this report:

Report Element Overviews and Findings

1. Barton Creek Watershed Ground Water Monitoring Program: 1993 - 1996

Purpose:

- Determine impact of urbanization on ground water quality and quantity for both baseflow and stormflow.
- Determine impacts of on-site and wastewater irrigation on ground water quality and flow.
- Identify characteristics of water quality and flow in Barton Springs and the Edwards Aquifer.

Overview:

Ground water monitoring in the Barton Creek Watershed focuses on ground water issues in both the Contributing Zone and Recharge Zone of Barton Springs. Contributing Zone efforts examine local ground water resources and problems due to the nature of the shallow water tables in the Contributing Zone. Recharge Zone or Edwards Aquifer studies are more area-wide in scale due to the complex nature of ground water recharge and movement in the Edwards Aquifer and the associated difficulty of identifying local development impacts. Current ground water monitoring efforts related to Barton Creek include the following:

- Water samples are collected and analyzed for nutrients, physical parameters, ions, and selected heavy metals from selected springs in the Barton Creek Watershed twice a year.
- Water samples are collected quarterly from five springs discharging from the Barton Springs segment of the Edwards Aquifer (Barton, Eliza, Old Mill, Backdoor, and Cold Springs) and analyzed for physical parameters, nutrients, ions, and selected heavy metals.
- Water samples are collected every two weeks from Barton Springs and analyzed for nutrients and total suspended solids.
- Ground water flow paths are identified in the Edwards Aquifer from specific points in Barton and Williamson Creeks through an interlocal agreement with the Barton Springs/Edwards Aquifer District (BS/EACD).
- *In situ* data recorders are used continuously in Barton Springs measuring water, pH, temperature, dissolved oxygen, specific conductance, turbidity, and depth. Data recorders are used periodically in other Edwards springs.
- Through a cooperative program with the U.S. Geological Survey (USGS), water samples are collected annually from numerous wells in the Barton Springs segment and Barton Springs.

Findings:

Ground water quality is generally good in springs monitored in the Glen Rose Formation and in the Contributing Zone of the Barton Springs segment of the Edwards Aquifer. However, statistically significant water quality differences in total dissolved solids, total Kjeldahl nitrogen, calcium, potassium, nitrate, sodium, chloride, sulfate, alkalinity, and total organic carbon have been identified in springs located in urban areas versus rural areas. One spring on the mainstem of Barton Creek, below the Lost Creek Blvd. bridge, has a significant effect on the nitrate concentrations in a localized area. The only identifiable source of the nitrates is leakage from effluent holding ponds and effluent irrigation in the immediate area. Nitrogen concentrations and isotope ratios at the holding pond and spring are similar. Increases in springflow resulting from wastewater irrigation on a tributary in Barton Creek West have also been indicated from monitoring data.

Nutrient and metal concentrations in Barton Springs do not show clear time trends that appear related to urban development. During 1981-82 under low discharge conditions when nitrogen concentrations are greatest, nitrate nitrogen averaged 1.54 mg/L compared to 1.46 mg/L in 1995-96 under similar conditions. However, impacts need not be continuous in order to be considered degradation, and the presence of tetrachloroethylene in Barton Springs water in the late 1980's and early 1990's indicates that the results of some urban activities can be seen in the springs. Several heavy metals, including arsenic, cadmium, copper, lead, nickel, and zinc, as well as sediment of possible anthropogenic origin also have been detected at Barton Springs. Old Mill and Cold Springs also appear to be affected by urbanization as indicated by heavy metals, pesticides, and total petroleum hydrocarbons. Comparisons of ground water chemistry made among five discrete spring sources (Barton, Backdoor, Eliza, Old Mill, and Cold) within the Barton Springs segment of the Edwards Aquifer show that Barton Springs and Backdoor Springs have the highest nitrate levels. These and other water quality differences among the five springs are commonly attributed to differences in recharge areas, land use, and flow paths to each spring. Barton, Eliza, and Old Mill Springs discharge into Barton Creek near its confluence with the Colorado River. They appear to discharge water recharged throughout the Edwards Aquifer. Cold Springs discharges into the Colorado River downstream of Red Bud Isle and receives water recharged in the Rollingwood area and Barton Creek. Backdoor Spring discharges to Barton Creek in the upper end of the Recharge Zone and appears to receive water recharged between Barton Creek and U.S. Hwy 290.

Many constituents like nitrate and various ion concentrations are *inversely* related to discharge rates at Barton Springs due to dilution with less concentrated recharge water, while suspended solids and bacteria concentrations are *positively* related to discharge rates due to contributions from surface runoff. Impacts to Barton Springs from rainfall in the Barton Creek Watershed generally have a lag time of approximately 14 hours, indicated by declining values in specific conductance and pH, and increases in turbidity and dissolved oxygen. Based on this lag time, ground water velocity of recharged storm water is estimated to average around 860 ft/hr. A data point indicating possible recharge from Williamson Creek reaching Barton Springs in sixty-five hours indicates ground water average velocity for storm water of approximately 400 ft/hr. Analysis of Edwards wells indicates that seven wells, in addition to Old Mill Spring, may be affected by urban development, based on nitrate, sulfate, and chloride concentrations. These sites are mostly in developed areas of the Aquifer. Barton Springs water quality is representative of the overall good quality of water recharging the Edwards Aquifer. Nevertheless, transient impacts to Barton Springs are affected most strongly by water quality changes in Barton Creek as shown by Datasonde parameter changes in water quality at Barton Springs following stormwater runoff to the creek.

2. The Barton Creek Pools Study: November 1990 - November 1995

Purpose:

The Barton Creek Pools Study was initiated to document existing ecological or water quality impacts to perennial pools due to current levels of development. The study is a comparison of baseflow water quality and an ecological assessment of nine pools along the mainstem of Barton Creek from the headwaters to the Edwards Aquifer Recharge Zone. Analyses of data are made to determine if statistically significant differences exist between pools for various water chemistry parameters and percent cover of filamentous algae, and determine if any trends in water quality degradation exist between developed and undeveloped reaches of the creek or if any water quality degradation is measurable over time.

Overview:

Since November of 1990, the City of Austin has monitored baseflow water chemistry and percent cover of filamentous algae growth at nine natural pool sites on the mainstem of Barton Creek, from the headwaters, upstream of Dripping Springs, to the Edwards Aquifer Recharge Zone, upstream of the Loop 360 bridge in Austin.

Aquatic vegetative cover, nutrients, suspended and dissolved solids, bacteria, and additional chemical and physical parameters were measured quarterly in each of the nine pools. Summary statistics and comparisons between pools were used along with field observations and comparisons to state-wide information to interpret the data. Several methods of handling non-detect data were examined for use in hypothesis testing.

Findings:

Comparisons made between pools in this study illustrate some small but statistically significant spatial differences in water quality along Barton Creek's mainstem; however, no temporal trends over the monitoring period were determined to be significant.

Surface water comparisons made among nine perennial pools over a five year period on the mainstem of Barton Creek indicate that the lower three study pools, all below Barton Creek Blvd. and along the most highly developed reach, are each impacted by either significantly higher nitrates, TDS, TSS, turbidity or algal growth. The other six pools upstream of Barton Creek Blvd. show no significant degradation with the exception of significantly higher fecal coliform at the most upstream headwater pool. It is important to note that many of the impacts to each of the lower three pools are localized and not ubiquitous along this lower reach of the creek. Water quality impacts seen at one study pool are remediated before reaching the next study pool, only to be replaced by other impacts potentially related to local land use or construction activities.

Baseflow water quality above Barton Creek Blvd. is fairly homogeneous, and from the data available the water chemistry along this reach of the mainstem has not deteriorated substantially since the 1988 Barton Creek Policy Definition Report was written. The baseflow water chemistry throughout the study area is still superior to urban streams contributing to Town Lake studied by the City's Water Watchdog Program. Baseflow water chemistry also compares favorably to least-disturbed streams studied by the Texas Natural Resource Conservation Commission (TNRCC) in the Central Texas Plateau ecoregion.

The highest nitrogen and TDS concentrations are found in one pool located below Lost Creek Blvd. Bridge. This elevated nitrogen and TDS is a result of contributions from a spring, possibly enriched through leaks in effluent holding ponds and effluent irrigation in the area. Similar stable nitrogen isotope ratios and nitrogen concentrations link the spring and effluent, but continued investigations, including dye tracing, and additional isotope testing would be necessary to verify effluent and/or fertilizers as a source.

The pool below Lost Creek Blvd., downstream of residential and golf course land uses, is significantly higher than all other sites in percent cover of filamentous green algae, principally due to reoccurring *Cladophora* sp. blooms there. Higher nitrates and conductivity correlate positively with higher filamentous algae at this site. ERM staff have also observed that massive *Cladophora* blooms can result from nutrient surges caused by accidental spills or mismanagement of domestic wastewater effluent used for irrigation.

Significantly high turbidity is measured at two sites, one just below Barton Creek Blvd. and one just above the Recharge Zone. The Recharge Zone site is also significantly higher in TSS. Intense local construction activity and upstream impoundments which trap and concentrate the fine sediments from construction sites are the only unique observable source for these elevated TSS concentrations. In general, higher TSS values were caused by an increase in mineral sediment load rather than organic sediment load as observed through VSS to TSS ratios.

Fecal coliform is significantly higher at the most upstream rural site (Pool 1); however, bacteria counts are still very low there compared to other urban creeks and normally within safe limits for recreational contact. If fecal coliform to fecal streptococci ratios are taken as adequate indicators, then fecal coliform is of animal, not human, origin throughout the watershed. However, since the start of the Barton Creek monitoring program the use of this ratio in determining origin has been determined to be less than definitive. Regardless, at Pool 1, the source of fecal coliform is most likely the cattle ranching operations upstream and adjacent to the sampling pool.

At present, these significant water chemistry differences are rather small and localized. During periods of good flow, enough relatively pristine waters are still contributed from Barton Creek's rural and undeveloped areas to dilute or remediate impacted discharges from developed tributaries and springs located lower in the watershed. The conclusions of this study are consistent with national data which indicates that documenting limited impacts are detectable in the current impervious cover range of the Barton Creek Watershed (Schueler, 1995). As Barton's Watershed develops and more impacted discharges are added, water quality degradation in Barton Creek will likely be more widespread and conspicuous.

Further development in the Barton Creek Watershed that does not provide adequate base flow protection and impervious cover limits will most likely be associated with the following impacts observed in the pool study sites during baseflow periods: (1) diminished water clarity in impounded and slower-moving waters, resulting from cumulative impacts of construction-related runoff; (2) replacement of a relatively diverse aquatic flora with a monoculture of *Cladophora* algae below lands with the potential for mismanagement of treated sewage effluent used for irrigation; (3) maintenance of heavier filamentous algae cover in the mainstem owing to nutrient-enriched waters draining to Barton Creek from developed tributaries and springs.

3. Barton Creek Canyons Study: 1993 - 1995

Purpose:

The Canyons Study was initiated to compare water quality impacts to tributaries of Barton Creek from different land uses and methods of wastewater disposal in their contributing watersheds.

Overview:

Data were collected from 38 sites on tributaries to Barton Creek. Three tributaries representative of each major land use are monitored monthly for baseflow water quality. Tributaries were categorized according to the dominant land use in their drainage area: golf course, high density residential, or rural (ranching and low density residential). Tributaries were also characterized according to the predominant method of wastewater disposal used in their drainage areas: golf courses using treated wastewater effluent for irrigation, residential areas irrigating with wastewater effluent on native land, residential areas on septic systems, residential areas on central sewage systems and rural areas with little or no commercial or residential development.

Parameters measured in the laboratory included nutrients, bacteria, and physical parameters. Summary statistics and non-parametric statistical tests were used along with field observations and land use information to interpret the data.

Findings:

There are significant differences in baseflow nitrate, ammonia, TDS, TSS, and turbidity concentrations between watersheds draining golf courses, residential, and rural land uses. Under most analysis groupings, golf course tributaries have higher constituent concentrations than residential tributaries, and both golf course and residential tributaries have substantially higher concentrations for these five parameters than rural tributaries.

Baseflow data, as indicated by antecedent dry conditions, suggest that nitrate nitrogen is the most variable parameter measured in the Barton Creek Watershed. A comparison of tributaries characterized by various wastewater treatment strategies reveal that golf course watersheds using sewage effluent irrigation and fully developed residential watersheds on central wastewater systems generate significantly higher nitrate concentrations in their baseflow than residential watersheds irrigating native vegetation/grass areas with sewage effluent, residential neighborhoods on septic systems, or undeveloped rural watersheds.

Buffers associated with residential areas using septic systems appear to be functioning to keep excess nutrients and bacteria from reaching surface waters. This finding may also be related to the lower impervious cover associated with larger lot sizes in residential areas on septic systems.

When water samples are collected simultaneously during storm events from the three selected tributaries representing residential (central sewer), golf, and rural land use, the representative golf course site is significantly higher in nitrates and ortho phosphorus than the other two land uses, while the representative residential site is significantly higher in pH and lower in TDS than the other two land uses. The residential site's lower TDS illustrates the dilution effect of heavier storm runoff experienced in land uses with more impervious cover.

Baseflow water quality samples collected contemporaneously from two adjacent residential canyons on central wastewater collection systems indicate that the size of the undeveloped buffer zone around a stream may be related to water quality. Median nitrate concentrations in these two canyons indicate that water quality improves as buffer zone size increases. Furthermore, impacts to pH are mitigated by larger buffer zones.

In summary, when compared to streams representing rural land use, various parameters indicate statistically significant water quality degradation for streams representing golf and/or residential land use categories. The level of significance for some parameters is influenced by the handling of values below the reporting limits in data analysis. In general, little impact was noted on study conclusions of group differences when alternate methods of handling non-detect data were employed.

4. Barton Creek Sediment Quality Studies: 1991 - 1995

Purpose:

Barton Creek sediment quality was assessed from a composite of various studies and investigations made by Austin's ERM staff to examine trends and compare contaminant levels to regulatory criteria.

Overview:

Sediment samples were gathered by five different project teams, each attempting to detect short and long term trends in the accumulation of heavy metals, organic pesticides and other organic constituents.

Findings:

Concentrations of sediment constituents throughout the Barton Creek Watershed are not at levels of concern with the exception of the area in and around Barton Springs. Polycyclic aromatic hydrocarbons were detected at levels which may have biological effects in the Barton Springs area. Although many potential pesticides were analyzed for, very few were found in detectable concentrations. However, one sample, immediately above Barton Springs, contained several organochlorine pesticides above the TNRCC 85th percentile, which is a regulatory screening level used in assessing sediment contaminants. Observed copper, lead, and zinc concentrations are elevated in the Barton Springs area relative to upstream sites; however, the highest chromium, cadmium, and zinc concentrations occurred in one sample taken at an upstream rural site. Grain size distribution indicates that higher concentrations of constituents at downstream sites could be attributed to the deposition of a larger percentage of fine-grain material.

5. Bioassessment Strategies for Nonpoint Source Polluted Creeks, Grant Funded Project: June 1993 - August 1996

Purpose:

The major goals and objectives of the study included investigation and documentation of current levels of physical and biological impairment in two watersheds (Barton and Onion Creeks) with varying degrees of development, correlation of various biological community conditions with physical and chemical indicators of nonpoint source pollution, and development of effective long-term biological monitoring and assessment techniques for the Central Texas region.

Overview:

Aquatic biological communities are typically sensitive to water quality and habitat degradation. "Bioassessment" methodologies have been developed and are now widely used which analyze these communities for use as indicators of stream health. For the purposes of this study, "benthic macroinvertebrates" an aquatic assemblage of snails, mayflies, stoneflies, blackflies, caddisflies, dragonflies, etc., were examined as well as a community of periphytic algae, the diatoms.

Following initial protocol development, project staff cataloged potential study sites by identifying reaches with appropriate habitat and substrate for benthic communities. After site selection, water quality, habitat, and biological data were collected at Barton and Onion Creek study sites on a quarterly basis for three years. Biological data were analyzed with corresponding water chemistry and land use attributes in order to document the relationship between the data sets.

Findings:

Development in Barton Creek is still in the early stages, with current impervious cover estimates in the bioassessment study reach at 6 percent. Onion Creek has impervious cover estimates of 10 percent in the study reach. The findings of this report suggest that the macroinvertebrate community is responding more dramatically to the water quality variation on Onion than on Barton Creek. It is likely that creeks with higher mean levels of water column nutrients than Barton may have a more consistent response to chemistry by the macroinvertebrate community.

Overall, the diatom community metrics are better than the benthic macroinvertebrate metrics at differentiating between different water chemistries and land uses. Consistent site level variation is more common in Onion Creek than in Barton Creek, suggesting that there is a minimum level of chemical constituent concentrations beneath which these biological metrics cannot effectively differentiate.

On both Barton and Onion creeks, diatom community changes are related distinctly to watershed changes due to levels of development as indicated by land use breakdown. On Barton Creek the diatom community is significantly responding to the land use change from undeveloped to golf course and residential land uses which begin downstream of Barton Creek Blvd. and continue down to Lost Creek Blvd.

From data collected in this study, the chlorophyll *a* mean concentrations are different between the land use groups on Barton Creek. Sites adjacent to and downstream of Barton Creek Blvd. with higher levels of residential housing and golf course land use had significantly higher chlorophyll *a* and pheophytin values than sites with lower levels of each of these land uses. However, the relationship of chlorophyll *a* and its surrogates to water chemistry data were not significant, suggesting that the measure of algal biomass through chlorophyll *a* is a more sensitive indicator of nutrient enrichment from nonpoint source pollution than routine chemical water quality sampling.

The radical fluctuation in flow rates during this study emphasized temporal variation in water chemistry concentrations and minimized the influence of spatial, or land use, differences between sites. Nonetheless, consistent relationships were identified between developed land use and two important water chemistry parameters - total dissolved solids and nitrate+nitrite nitrogen.

Although overall nutrient concentrations on Barton Creek were not significantly different from upstream to downstream due to high standard deviations, all of the highest values and highest means were recorded between Barton Creek Blvd. and Lost Creek Blvd. In general, the macroinvertebrate data from the Bioassessment Grant indicate that current levels of biological impairment in Barton Creek are extremely low.

6. Barton Springs Ecological Surveys and Projects: 1993 - 1996

Purpose:

Ecological descriptions and studies made by City staff at Barton Springs pool include an inventory of fauna and flora, salamander population studies, and pool revegetation projects.

Overview:

In addition to monitoring the pool salamander population, ERM staff are involved with monitoring the general ecology and habitat quality of Barton Springs. On a yearly basis, the vascular vegetation in Barton Springs is inventoried and expanded by dissemination of existing stands of plants in the pool and transplanting of local populations from Barton Creek and Town Lake.

In conjunction with the salamander monitoring program, ERM staff has been closely involved with the City's Parks and Recreation Department and their maintenance practices at the pool. Sedimentation, slipperiness due to algae growth, and algae blooms have all been maintenance issues since monitoring of the salamander began over three years ago. Staff members have initiated studies to research and develop maintenance practices that benefit the salamander, the citizens of Austin, and the pool staff. All available salamander data are verified, tabulated, stored in the Drainage Utility database, and made available to the public.

Findings:

The Barton Springs salamander population counts have fluctuated from 1 to 45 individuals since 1993. Counts can be most dramatically affected by large storms and subsequent high turbidity and sedimentation. Anecdotal records indicate that the current surface population in the main springs is a small fraction of populations from the early 1980's and before. The Barton Springs salamander is responding to obvious environmental changes, but the more subtle chemical and physical changes that affect this organism have yet to be determined. Efforts to establish viable captive populations for research have met with limited success at the Dallas Zoo and the Midwest Science Center in Columbia, Missouri.

Aquatic plant community revegetation efforts in Barton Springs pool have been successful and include stands of *Potamogeton*, *Sagittaria*, and *Ludwigia* aquatic plant species. These varieties provide excellent habitat for aquatic life in the pool while reducing turbidity by stabilizing sediments. After three years of effort by City staff and citizen groups, and following maintenance changes by PARD staff, the aquatic vegetation in Barton Springs is returning. In 1993, vegetative cover was estimated at 1 %. Today it measures 7 %, and more proactive efforts are planned.

7. Barton Creek Watershed Surface Water Model

Purpose:

The general purpose of the modeling effort was to develop a tool capable of explicit representation of the physical processes governing water quantity and quality in the Barton Creek Watershed. Such a tool would be useful for predicting the impact to water quality of various land use scenarios. The focus of this modeling effort was the application of the industry standard Stormwater Management Model (SWMM) to the Barton Creek Watershed. Because of SWMM ground water routine limitations, only the portion of the watershed above the Recharge Zone was simulated.

Overview:

This project was initiated with technical assistance from a consultant advisory contract and completed through City staff and assistance from the Drs. Randall Charbeneau and Michael Barrett of the University of Texas at Austin Center for Research in Water Resources. Several mid-course changes in analysis methods and approaches were made in this project, but the major tasks conducted included a statistical analysis of mainstem water quantity and quality data from USGS stations on Barton Creek, baseflow separation from the same gages, SWMM input file development for both Barton Creek and single land use watersheds, and attempted calibration and verification of the models. Flow validation of SWMM for both Barton Creek and single land use watersheds was conducted with some success. Attempts at water quality calibration of SWMM models for both Barton Creek and single land use watersheds were met with limited success. Evaluation of the underlying assumptions of the SWMM water quality model formulations using single land use watershed data was performed. Development of a statistical model alternative for simulation of Barton Creek existing conditions was successful; however, limited predictive utility was anticipated for the model.

Findings:

The USGS/City of Austin joint monitoring program provides data for evaluating water quality along Barton Creek. In general, water quality is good. Available water quality data for three stations along Barton Creek were analyzed using baseflow separation from gaged flows, and it was determined that mean values for most of the constituents are higher during storm flow conditions than for baseflow conditions. Total suspended solids (TSS), which is the most widely considered indicator of stormwater quality, has an average concentration which is two orders of magnitude larger under storm flow conditions when compared with baseflow conditions. Both the storm flow mean TSS concentration and its variability increase for downstream stations along the Creek. The storm flow mean TSS concentration at Loop 360 is more than double that at Highway 71 and Lost Creek stations.

The parameters positively correlated with some significance to flow in stormflow conditions included biochemical oxygen demand (BOD_5), total organic carbon (TOC), fecal coliform (FCOL), fecal streptococcus (FSTR), ammonia nitrogen (NH_3-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), total suspended solids (TSS), total lead (TPb), and dissolved zinc (DZn). All the water quality constituents which are correlated with flow, except total lead, have average concentrations which are greater at Loop 360 than at the other monitoring stations. One explanation of these increases is the greater amount of impervious cover at the lower end of the Barton Creek Watershed. In addition, BOD_5, TOC, FCOL, FSTR, and total nitrogen have average concentrations which are one to two orders of magnitude larger during direct runoff conditions than during baseflow. Nitrate + nitrite is higher progressing downstream in stormflow; however, in baseflow it is constant at Lost Creek and Loop 360, and lower at Hwy 71. Ammonia is constant in baseflow yet increases slightly downstream in storm conditions. TKN is significantly higher progressing downstream in stormflow, and modestly higher in baseflow. Further, the mean TOC concentration at Loop 360 more than doubles that at Highway 71 and Lost Creek under stormflow conditions. The average TDS concentration is larger for baseflow than for storm flow conditions at all three stations due to runoff dilution, with greatest concentrations at the Lost Creek station. Correlation analysis shows that TSS, BOD_5, TOC, TKN, FCOL, FSTR, TP and TPb all increase with runoff, while only NO_2+NO_3 is inversely related to runoff. The other water quality parameters are insignificantly correlated to the runoff magnitude.

Ideally, the results from the surface water quality model were to be used as simulation input to the ground water model in order to predict the impact to Barton Springs discharge water quality under a variety of land use scenarios. Due to the complexity of the system modeled and the limitations of the available model formulations, water quality was not predicted well although a statistical formulation allowed simulation of historical conditions. However, water quantity may be simulated well enough by SWMM to provide a basis for input scenarios to the ground water model using land use based mean concentrations from the City of Austin Storm Water Monitoring Program. This use of the model is under investigation in association with the Drainage Utility City-wide Masterplan.

The overall conclusion from the investigation of the single land use data is that industry standard public domain watershed models are not able to adequately predict the accumulated stormwater load on the watershed at the beginning of a runoff event, nor the initial constituent concentration provided by the City of Austin Storm Water Monitoring data. The model does a better job of representing the washoff processes. Thus, SWMM may be a useful quality model for simulating single storm events, but our understanding of the various processes which control the quality of urban runoff does not allow us to model a continuous series of events in Barton Creek with SWMM or any other comparable model using buildup/washoff as a basis.

8. CRWR Barton Springs Edwards Aquifer Ground Water Model

Purpose:

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 aquifer water quality and availability.

Overview:

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 corresponding to the five major creeks supplying recharge to the aquifer. Each of the cells 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 ground water models.

Findings:

Data analysis performed for this study did not detect changes in the water quality of Barton Springs over the last 15 years. This can be attributed to several factors. Impervious cover in the Contributing and Recharge Zones accounts for only five to eight percent of the total area and has changed relatively little over the period of study. 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 data. 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.

Development simulated in the model reduced the baseflow while it increased the peak flow rates during periods of direct runoff. Baseflow reduction resulted in lowering the average discharge at Barton Springs between 11 and 34 percent. The increase in impervious cover of the watersheds resulted in more recharge during what would normally be extended periods of no recharge so that the average minimum spring discharge remained unchanged.

Predicted increases in peak flows may also result in more frequent Barton Springs Pool closings owing to flooding of the pool by Barton Creek.

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. These parameters may be investigated using the model during the development of the Drainage Utility City-wide Masterplan.

Using the data from more urban creeks, a level of intense development (45 percent impervious cover) was estimated to raise the predicted nitrogen concentration at Barton Springs from about 1.5 mg/L to approximately 3.5 mg/L, an increase of 130 percent. A moderate level of development (20 percent impervious cover) increased the predicted nitrogen concentrations at Barton Springs from 1.5 mg/L to 1.8 mg/L, an increase of approximately 20 percent. 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. Nitrogen accounting performed as part of this project estimated that septic systems contribute about ten percent of the nitrogen input to the aquifer. An increase in septic system use was not projected to be a problem, assuming development doesn't reach a level such that storm water runoff from these sites reduces the quality of the water in the creeks as well. The greatest impact from higher nitrogen concentrations may be on Barton Springs Pool and Town Lake, where the increased nutrient supply will promote the growth of algae and eutrophication. This potential is under investigation as part of the Drainage Utility masterplan.

From analysis of extreme levels of development in model simulations, 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 under normal rainfall conditions.

Continued population growth and reliance on the aquifer for drinking water may result in greater reduction of flow when a severe drought occurs. Low spring flow may pose a serious threat to the Barton Springs Salamander and affect the operation of Barton Springs Pool which draws over 300,000 swimmers annually.

Changes in land use in the Barton Creek Watershed are most likely to be evident at Barton Springs Pool. Changes in water quality in the Pool will probably be larger during recharge events than the average change predicted by the ground water 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 is predicted to 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. Closures due to pool flooding are also projected to become more frequent due to increase in the magnitude and number of peak flow events.

9. Barton Springs Contributing Zone Retrofit Masterplan

Purpose:

The goal of this project was to evaluate the historical water quality in the Barton Springs Zone (BSZ) and recommend a cost effective strategy for water quality retrofit implementation in previously developed areas of watersheds crossing the Recharge Zone.

Overview:

The retrofit masterplan consisted of a water quality analysis and a retrofit analysis. The water quality analysis included review of all pertinent data in the BSZ and some limited modeling evaluation of pollutant loading from conventional on-site systems and rangeland management. Storm water monitoring data were used to predict loadings by land use and generalized removal efficiencies of BMP's were used to evaluate retrofit strategies.

Findings:

Although the assessment of current conditions indicated that water quality was, "with a few significant exceptions... excellent", observable or measurable degradation in the BSZ was determined to include "statistically discernible increases in mean constituent concentrations in stormflow and baseflow at creek locations in the more developed basins, pockets of algae growth, apparent staining of rocks in areas draining roadways, several significant erosion sites, unusual accumulations of trash and debris, and sedimentation and toxics accumulations measured in some wells" (Loomis, 1995). Primarily TSS and TN were used as indicators of water quality in the BSZ retrofit masterplan.

The sources proposed to explain the observed water quality degradation in the BSZ included urban runoff, in-channel erosion, construction related sediment, septic systems, effluent irrigation, and rangeland degradation. Implementation of major structural retrofits was proposed at 26 sites yielding an estimated 4.5 percent reduction in TSS loading and 3.1 percent reduction in TN loading to the BSZ at a cost of $11 million. These sites are to be considered in the City-wide masterplan in order to prioritize all retrofit construction for future Drainage Utility projects. Smaller, site specific structural controls were found to provide less of an impact than regional controls. However, non-structural controls researched including regulatory and public education approaches were estimated to have a potential significant impact on minimizing degradation in the watersheds of the BSZ. A number of additional recommendations were made in order to better manage water quality in the BSZ.

Overall Conclusions and Recommendations

Many localized impacts to developed springs and tributaries have been verified or identified within the Barton Creek Watershed through the City of Austin monitoring projects. Effluent irrigation spills, a form of point source pollution, are believed to have caused some abnormally dense *Cladophora* algae blooms along the mainstem of Barton Creek; but to date, the nonpoint source pollution load is not gross enough in the mainstem of Barton Creek to disclose substantial decline over the monitoring period through either chemical, biological, or physical measurements. However, the comparisons made between developed and undeveloped areas in the pools, canyons, and springs of the watershed indicate ongoing changes in water quality. Combined with episodic contamination events these differences can be said to represent localized degradation. The complexity of hydrology, geology, and ecology in Barton Creek obscures easy and early identification of impacts to the mainstem. Therefore, continued monitoring is essential to diagnose the on-going health of this important system. Through Drainage Utility funding, the City of Austin's Environmental Resources Management Division has developed ground water, surface water, sediment, and biological monitoring strategies to keep policy makers and citizens informed of any significant water quality trends jeopardizing this resource.

Recommendations for future monitoring on Barton Creek include routine comparisons with more developed watersheds; long term water quality tracking in developing subwatersheds; enhanced baseflow and stormwater monitoring on the mainstem, select tributaries, and springs; development and implementation of workplans for comprehensive collection and analysis of sediment and biological data on the mainstem, select tributaries, and around Barton Springs; tracer studies to determine the source of ground water contributions over the Edwards and Glen Rose formations, and further use of parsimonious ground water and surface water models in conjunction with the Drainage Utility City-wide masterplan.

Recommendations for policy focus which are indicated from the studies documented in this report and national data from similar studies include the following:

- Intensive easement acquisition in the mainstem and tributaries of Barton Creek to secure water quality benefits offsetting the bulk of the watershed which is out of COA ordinance jurisdiction.
- Expansion of the Barton Creek wilderness area as a buffer zone to provide a larger recovery area offsetting projected headwater development.

- Requirements for additional golf course water quality buffers to be added to ordinance restrictions.
- Formulation of a coordinated set of guidelines for effluent land application for the BSZ to be proposed to TNRCC as special conditions of irrigation disposal, during the basin-wide permit renewals scheduled for 1999.
- Flood control regulatory modifications to correct erosive influences of flood control structures constructed under current requirements if indicated from a proposed technical review.
- Infiltration device construction and promotion of infiltration to be implemented through regulation and policy changes.
- Implement Drainage Utility policies considering repercussions of altering natural flow patterns as a criteria in decision making.
- Develop and implement a specific watershed scale land use regulation of the Barton Creek Watershed.

1.0 INTRODUCTION

Barton Creek's water quality is a topic of immense interest to the citizens of Austin, Texas. Austin's concern to keep these waters pristine is of top priority and represents the people's commitment to protection of the region's environmental resources as a whole. The watershed of Barton Creek is over ten times the cumulative size of the eight other creek watersheds that contribute waters directly to Town Lake. These eight other watersheds contributing to Town Lake are fully developed, and the City of Austin is striving to improve the water quality of these streams through retrofit with structural water quality controls, community education, and an Urban Watersheds Ordinance. In contrast, Barton Creek's waters are only beginning to show signs of degradation, and can still benefit from management strategies aimed at preventing pollution.

The relatively high quality of Barton Creek's waters is due to the vast portion of the Watershed that remains undeveloped, the City's purchase of greenbelt, and the succession of water quality ordinances passed by Austin citizens and the City Council. These ordinances, which apply only over the portion of the Barton Creek Watershed within Austin's extraterritorial jurisdiction, have provided for regulation of density and impervious cover, the capture and treatment of stormwater, and the protection of critical water quality zones and sensitive environmental features. Applicability of these ordinances is now contingent upon date of development application (SB 1704) and formation of privately managed Water Quality Protection Zones (30 TAC 216), which further subdivide regulatory jurisdiction of the watershed. Without strong and enforceable protection for the entire watershed, the fate of Barton Creek's water quality may be the same as other urban watersheds which have developed without regulation or land use planning.

An important aspect in investigating water quality in the Barton Creek Watershed is the interaction that occurs between ground water and surface water. Glen Rose ground water systems are extremely important to providing baseflow to Barton Creek through spring discharges and alluvial seepage. As the soft marl steps of the Glen Rose geologic formation are saturated by Hill Country rain, this precipitation is stored and slowly released as Barton's baseflow. Seeping to the surface, deep within the canyons of a highly dissected landscape, this original Glen Rose filtrate works its way through Barton's headwater tributaries. Owing to these wide spread contributions, a healthy, perennial flow is normally maintained in the mainstem of Barton Creek. However, along the final few miles before reaching Town Lake on the Colorado River, Barton's surface waters run across the Edwards Aquifer Recharge Zone where much, and sometimes all the water drops into karst formations to emerge later as cool and abundant Edwards Aquifer spring water.

Unique biological niches are formed in conjunction with Barton's ground water - surface water interaction zones. In the upper part of the watershed, Glen Rose seepage drips from the faces of fern- and moss-lined grottos. These grottos are often distinguished by waterfalls and plunge pools. Mesic vegetation communities, including dwarf palms, maidenhair ferns, and moisture-loving liverworts, thrive in these refuges. Further downstream, springs may gush from hard limestone fissures of the Edwards formation, or surface waters are captured by the Edwards Aquifer in a swirling vortex created by solution cavities in the creekbed. The discharge point of the Edwards Aquifer is Barton Springs, home to the rare Barton Springs salamander and 300,000 swimmers annually. The quality of water coming from Barton Springs and therefore the survival of these unique creatures is directly dependent on the health of the streams that feed the Edwards Aquifer.

This report is divided into four major fields: ground water studies, surface water studies, bioassessments, and modeling. All four of these major sections address the water quality impacts from various types and intensities of development over the Barton Creek Watershed. Ground water studies include assessments of spring water quality within the Glen Rose geological formation or the Contributing Zone to the Edwards Aquifer, and assessments of water quality in springs and wells within the Edwards Aquifer, including Barton Springs. Surface water studies include an assessment of water quality and algae growth along Barton's mainstem from the headwaters to the Recharge Zone, an assessment of water quality in Barton Creek tributaries characterized by land use, and an analysis of sediment data collected throughout the watershed. Bioassessment studies include a summary of a grant awarded to the City to study the effects of nonpoint source pollution on aquatic organisms in Barton and Onion Creeks, a status report on population inventories of the Barton Springs salamander, and an inventory of the fauna and flora found in Barton

Springs pool. The final major section summarizes the findings from ground water and surface water models, constructed to predict future impacts from development and presents the findings of a planning document concerning the design of water quality retrofits for the developed areas of the watershed. The combination of information in these four major areas gives the reader a comprehensive account of the state of the environment for the Barton Creek Watershed.

2.0 GROUND WATER SYSTEMS OF THE BARTON CREEK WATERSHED

2.1 INTRODUCTION

2.1.1 Purpose

The Drainage Utility Department (DUD), formerly the Environmental and Conservation Services Department, of the City of Austin (COA) monitors ground water quality in the Barton Creek Watershed. Monitoring goals include characterizing overall ground water quality in Barton Creek as well as determining baseline water chemistry in rural areas and determining the effects of urbanization on ground water chemistry. The primary means of ground water monitoring is collection and chemical analyses of spring samples. Well sampling is also conducted in the Edwards Aquifer to provide additional data on ground water quality. Data on ground water yields were compiled from COA surface water studies described in Section 3.0.

The Barton Creek Watershed encompasses 120 square miles, eight of which are in the Recharge Zone of the Barton Springs Segment of the Edwards Aquifer (BSEA) and 112 square miles are in the Contributing Zone of the aquifer (Santos, Loomis and Associates, 1995). The Edwards Aquifer is vulnerable to pollution because of the rapid movement of water into the subsurface through recharge features such as faults, fractures, sinkholes, caves, and open holes within bedrock. In the Recharge Zone, recharge features in creek beds permit rapid transmittal of water flowing in Barton Creek into the aquifer.

2.1.2 Methodology

Ground water monitoring in the Barton Creek Watershed is conducted primarily at springs identified by City of Austin staff, landowners, and in published material. Some springs included in this report were sampled once, while others are sampled on a regular basis. Sampling locations are shown on Plate 1.

Data sources used in this report for Edwards springs include COA/Drainage Utility Department (DUD), COA/Austin Travis County Health and Human Services Department

(ATCHHSD), and the United States Geological Survey (USGS). Specific data from previous studies are included where appropriate. DUD data include field data, grab samples from springs under various flow conditions, and data from multiprobe data loggers installed in the springs. ATCHHSD, since the early 1980s, collects samples primarily for bacteria tests and has occasionally included other basic water quality parameters. The USGS, in cooperation with COA, collects samples from wells and springs in the Austin area since 1986. Data for springs other than Barton are much more limited but include data from COA/DUD, Barton Springs/Edwards Aquifer Conservation District (BS/EACD), Texas Water Development Board (TWDB), and graduate student theses.

2.1.2.1 Field Analyses

Field measurements of pH and total dissolved solids taken before March 1995 were made using Hach portable pens. Temperature was measured with a mercury or alcohol thermometer. A Horiba U-10 water quality meter has been used since March 1995. Field measurements made with this instrument include pH, specific conductance, turbidity, dissolved oxygen, and temperature. At the time of sample collection, these measurements are recorded on a field data sheet. Also recorded are descriptions of the spring flow, mesic vegetation at the spring site, and observations related to discharge. Estimates of spring discharge, made at the time of sample collection, are visual examination of the flow volume or direct measurement of the rate at which water fills a container of specific volume.

To help understand the complicated dynamics of Barton Springs and transient responses to storm events, the COA began using multiprobe data loggers in the springs. The COA selected a DataSonde 3 multiprobe logger manufactured by Hydrolab Corporation of Austin for *in-situ* monitoring of Barton Springs water. The DataSonde 3 simultaneously monitors temperature, pH, dissolved oxygen, specific conductance, turbidity, and depth. The sensitivity of the probes allows detection of very subtle changes in the monitored parameters. The unit selected has an internal battery pack, can be programmed to record at any specified time interval and store data internally for later downloading. The unit can be deployed and left unattended for approximately four weeks. The lack of external cables makes the DataSonde ideal for deployment in a high use facility like Barton Springs Pool.

2.1.2.2 Sample Protocols

Sample collection is done using precleaned one liter Nalgene bottles provided by the analytical laboratory or sterilized Whirlpak bags. Samples are collected as close as possible to the point of discharge from the rock or alluvial face. Samples are iced down in a cooler for transport to the lab. Chain-of-Custody forms are completed to transfer samples to lab custody.

2.1.2.3 Laboratory Analyses

Grab samples are collected for water quality analyses. Some analyses of nitrate-nitrogen, ortho-phosphate, and ammonia-nitrogen are performed in the DUD in-house laboratory using a Hach DR 2000 spectrophotometer. Most samples have been analyzed by the Walnut Creek Environmental Laboratory operated by the City of Austin's Water and Wastewater Department (COA/WWW). Other laboratories which have analyzed spring samples include Inchscape Testing (NDRC in Dallas, Texas), NET, Inc. in Austin and in Dallas, Lower Colorado River Authority (LCRA), and Coastal Science Laboratory. All analyzed parameters are listed in Appendix C. Parameters analyzed for each site vary owing to the entity collecting the sample, modifications in the COA ground water monitoring program, and specific concerns at some sites. All methods of analysis adhere to protocols published in Standard Methods for the Examination of Water and Wastewater or EPA method protocol. Quality Assurance/Quality Control data are included with results of analyses by each laboratory.

Standards of Chemical Quality have been established by Title 30, Sections 290.103 and 290.113 of the Texas Administrative Code and are regulated by the Texas Natural Resource Conservation Commission (TNRCC). Primary standards, promulgated in Section 290.103, establish the maximum concentration level (MCL) allowable in drinking water for inorganic chemicals, fluoride, and organic compounds. Secondary standards, set forth in 30 TAC 290.113, establish maximum concentrations for additional chemicals not included in the primary standards. These standards are provided in Appendix E. The City of Austin analyzes ground water samples for selected chemicals listed in the primary standards. Parameter selection balances health and environmental hazards with sample costs. The resulting list of analytical parameters includes nutrients, major ions, and several heavy metals. Comprehensive suites of organic compounds are too costly to test for on a regular basis at all springs. Drinking water standards are used only as a guide or reference point for ground water results; environmental impacts occur at far lower constituent concentrations.

2.1.2.4. Data Quality Assurance

The results of laboratory analyses of ground water are evaluated for accuracy. Approximately 10 percent of samples collected are field duplicates. Duplicates are compared for consistency. Constituents with wide deviation are omitted. Outliers are evaluated by examining previous data from the sites or data from similar sites. A charge balance calculation (comparison of the sum of the cations to the sum of the anions) is done for each ion analyses. The equation is:

$$\frac{\text{sum of cations - sum of anions}}{\text{sum of anions + sum of cations}} * 100 = \text{charge balance}$$

Hounslow (1995) recommends that only analyses with a charge balance less than five percent be accepted. However, few of the available spring sample analyses meet this criterion. Contract laboratories generally have broader ion balance ranges than research laboratories. Twenty-five percent was selected as the cutoff limit for acceptance of analyses. The range of charge balances for the Contributing Zone sample set is 0.969 to 1.253, within the 25 percent cutoff.

Review of the nitrate concentrations indicated possible errors in samples analyzed by the City of Austin's Walnut Creek Laboratory, Inchscape (formerly known as NDRC), NET, and LCRA. Concentrations reported by these laboratories were sometimes an order of magnitude greater than the concentrations determined using a portable spectrophotometer (Hach DR 2000) in the DUD laboratory. DR2000 data were consistently more accurate with standards and duplicates compared to COA/WWW Lab data during early phases of the ground water program. In some cases, DR2000 data were used in place of lab data for statistical evaluation.

2.1.2.5 Statistical Analyses And Evaluation

Ground water analyses for Contributing Zone springs were grouped as rural or urban for the purposes of statistical evaluation. Springs located in areas near and down gradient of residential, commercial, and industrial buildings and grounds were classified in the urban group. Springs found in nature preserve areas or ranches away from most land disturbances were in the rural group. Parameters provided as input for the statistical evaluation are provided in Table 2.1. Table 2.2 summarizes site information for Contributing Zone springs. The in-house, Water and Wastewater, and contract laboratories are currently being compared on the basis of accuracy and precision through blind standards analyses.

Table 2.1. Parameters For Statistical Evaluation

Total Dissolved Solids	Alkalinity
pH	Nitrate + Nitrite - Nitrogen
Calcium	Total Kjeldahl Nitrogen
Sulfate	Ammonia - Nitrogen
Sodium	Orthophosphate-P
Magnesium	Total Phosphate
Chloride	Chemical Oxygen Demand
Potassium	Total Organic Carbon
Fluoride	

Several tests were conducted on parameter concentrations. Analysis of variance was conducted using the General Linear Models (GLM) procedure in SAS since it is appropriate for unbalanced data sets. Less than half of the data had reported concentrations for each parameter.

The procedures were as follows:

1. Test the data for normality.

2. For normally distributed data, conduct a statistical analysis of variance (ANOVA) test for differences between means. If the test indicates significantly different means, conduct multiple comparison tests. Use Duncan's multiple-range test to give more detailed information about the differences among the means. Use contrast statements to provide customized hypothesis tests.

3. Rank the non-normal data.

4. Conduct an analysis of variance for significantly different means on the rankings. This is equivalent to a non-parametric test for differences between the means. If the test indicates significantly different means, conduct comparison tests. Contrast statements to provide customized hypothesis tests for the ranked data were used.

5. The non-parametric Kruskal-Wallis Test was conducted for comparison to the analysis variance test on the ranked data, with the same results.

A significance level of 0.05 was used for identifying statistically significant differences between the urban and rural groups of data. Values of one-half detection limits were used for statistical analysis of non-detection results. Additional hypothesis testing was performed using non-parametric comparisons with the ranked data censored at the highest detection limit for comparison. The results of the statistical analyses are discussed in Section 2.4.

Ion data were plotted on Piper diagrams to classify the waters chemically and determine if there were differences across the data sets or within specific sites. Piper plots are commonly used to study water chemistry and classify ground water types. Time series analysis was used to evaluate data from continuous data-recorders. Flow data were examined using time series analysis and yield techniques.

TABLE 2.2
Contributing Zone Springs Site Summary

BCR REPORT SITE NUMBER	CULTURAL CLASSIFICATION	GEOLOCIC FORMATION	POSSIBLE POLLUTANT SOURCES
55	Urban	Glen Rose/Terrace	Cattle, fertilizers, effluent irrigation
72/73	Urban	Terrace	Fertilizers, effluent irrigation, roadway
62	Urban	Glen Rose/Terrace	Fertilizers, effluent irrigation
44	Urban	Terrace	Fertilizers, septic leachate
76	Urban	Glen Rose	Fertilizers, effluent irrigation, roadway
35	Urban	Glen Rose	Fertilizers, effluent irrigation, pesticides/herbicides, wastewater exfiltration
36	Urban	Glen Rose	Fertilizers, effluent irrigation, pesticides/herbicides, wastewater exfiltration
38	Urban	Glen Rose	Fertilizers, effluent irrigation, pesticides/herbicides, wastewater exfiltration
8	Rural	Terrace	Cattle, septic leachate
32	Rural	Glen Rose	Roadway
13	Rural	Glen Rose	Cattle
12	Rural	Glen Rose	Cattle
14	Rural	Walnut	Cattle
17	Rural	Glen Rose	Cattle
39	Rural	Glen Rose	None

Source: COA/DUD Database

Bivariate analysis was conducted to determine relationships between parameters and to identify trends within individual site data sets. Data were examined for individual sites as well as grouped together since one of the goals was to determine impacts caused by urbanization. An urban signature for ground water identified in the Bull Creek Watershed was used as a model for bivariate analysis and builds on the use of bivariate plots to identify ground water sources in the Edwards Aquifer as used by Senger (1983), Senger and Kreitler (1984), and Hauwert and Vickers (1994). The boundaries established in these diagrams are used for examining springs in both the Contributing and Recharge Zones later in this section.

2.2 HYDROGEOLOGIC SYSTEMS OF BARTON CREEK

Springs found in the Barton Creek Watershed discharge from three hydrogeologic systems: the Glen Rose limestone in the Contributing Zone, Terrace/alluvial deposits in the Contributing Zone, and the Georgetown and Edwards limestones in the Recharge Zone. The rates of recharge differ within each system. Differences in recharge capacity of each system are evident in the variation in spring discharge rates, which, based on field measurements and published data, range from less than one gallon per minute (gpm) to 10 gpm in the Contributing Zone, based on field measurements, to over 22,000 gpm in the Recharge Zone for Barton Springs (USGS, 1995).

Barton Creek is a gaining creek (water flows into the channel from surrounding strata) in the Contributing Zone, fed by springs flowing from shallow water tables in the Glen Rose limestone and terrace deposits adjacent to creek channels. Over the Recharge Zone, flow in Barton Creek is available to recharge the Barton Springs segment of the Edwards Aquifer once it crosses the Mt. Bonnell Fault, the western boundary of the Recharge Zone. Here Barton Creek becomes a losing creek (water flows from the channel into the surrounding strata) with substantial volumes of water, up to 250 cfs (Barrett and Charbeneau, 1996), entering the underlying aquifer. Barton Creek near Barton Springs changes from losing to gaining depending on water table elevations in the aquifer.

Ground water discharges to creeks and tributaries at discrete points (springs) or as diffuse discharge along the banks, and channel bottoms. Spring discharge is important because it provides base flow, maintains pool levels in Barton Creek, provides fresh water input, and contributes nutrients to the ecosystem. Temperature differences in the water can help identify areas of ground water discharge from springs. In the summer, ground water discharges are cooler than surrounding waters, but in the winter, as surface water temperatures drop, ground water discharges are warmer than surrounding waters. Biological habitats benefit from the constant temperature of the spring flow.

The volume of ground water discharged as baseflow varies as climatic conditions change. During periods of drought, the contribution of ground water to baseflow drops considerably. Some pools of Barton Creek receiving perennial flow can survive dry periods, although the pool volume is reduced substantially.

2.2.1 Glen Rose Formation Hydrogeologic System

Springs which issue from the limestones and dolomites of the Glen Rose Formation are found at the head of incised drainages, along rock walls of drainages, and at bedding plane contacts. Some perennial springs are found in the Contributing Zone, but most springs of the Glen Rose are ephemeral. Springs may be identified during dry conditions by mesic vegetation and pool areas which form below the point of discharge. Typically, the discharge rate of Glen Rose Formation springs ranges from less than one gallon per minute (gpm) to approximately three gpm. Discharge rates are highly dependent upon antecedent weather conditions and may vary substantially from the measurements reported here. Some springs appear to sustain relatively high discharges because of frequent irrigation in their recharge area.

The most common zone of spring discharge is the base of the porous Member 3 dolomitic limestone layer (Rodda and others, 1970) of the Glen Rose Formation. This observation is based on locations of numerous springs in the Barton Creek Watershed downstream of Hwy 71 and in the Lake Austin Watershed. This 70 foot-thick nodular dolomite and dolomitic limestone has a honeycombed texture which permits rapid flow of infiltrated rainwater into the surface of the exposed rock. The water travels through the inter-connected pores to emerge at the base of Member 3. The grainy texture of the dolomite functions similarly to a sand body and can transmit water readily even in the absence of a honeycombed texture (Woodruff, 1993). The base of Member 3 is found from generally 40 to 100 feet above the main branch of the creek and outcrops over large areas in tributary watersheds.

The occurrence of ground water is highly localized and typically provides only modest volumes of water. Ranchers using wells for stock watering or to maintain the water level in a stock tank are typical consumers of these shallow resources. Because of the isolated nature of the local, shallow ground water systems, it is difficult to determine regional rates of ground water infiltration and subsequent discharge. Woodruff (1993) describes the occurrence of ground water in the Barton Creek Watershed as follows:

> Streams are commonly incised into narrow valleys and canyons with high-gradient ephemeral tributaries feeding main watercourses that are cut deeply enough to receive locally sustaining ground water discharge. Ground water occurs erratically from multiple horizons at relatively shallow depths.

The stair-step topography of the Hill Country, with its alternating hard limestone/dolomite beds and soft marly beds, is an important component of Hill Country hydrology. Recharge to shallow ground water bodies, the source for spring discharge in the Contributing Zone, occurs primarily as infiltration of rainwater to soils. Woodruff (1993) identified two hydrologic units in an area of the Barton Creek Watershed: uplands and bottomlands. Upland units operate as discrete areas of infiltration during low to moderate-magnitude rainfall events. Rainwater infiltrates the soils on the "risers," the steeply sloping break in soft marly beds and below hard resistant limestone beds, to form shallow ground water lenses. Infiltration rates measured by Wilding (1993) in an area within the Contributing Zone of the Barton Creek Watershed range from 0.8 inches per hour to 5.8 inches per hour. Higher infiltration rates occurred in areas with thicker soils and more litter or vegetative cover. Infiltrated water moves downward in short stair-step paths, through the riser soil to the hard underlying tread and then laterally to discharge as seeps. Water may enter the next lower riser or enter ground water lenses adjacent to drainages. In the bottomlands unit, infiltration to alluvial materials occurs following rain events. Infiltrated water within the sands, silts, and gravels forms a shallow, regional, somewhat contiguous body of ground water. The bottomlands unit is found primarily along the main channel of Barton Creek and large tributaries (Woodruff, 1993).

This stair-step hydrologic system forms a series of shallow ground water reservoirs in which water is slowly released to drainages or utilized by grasses and trees. Infiltrated rain water may pass through several stair-step systems before reaching surface water, each time filtering through soils and grasses. This hydrologic mechanism in the Hill Country has important implications for stream hydrology (short term water storage) and land management (minimizing disturbance impacts and maximizing natural filtration of runoff).

The elevation of the localized, shallow ground water tables like those found in the Glen Rose Formation tend to mimic the surface topography. Therefore, when attempting to determine the recharge area, the extent of the surface water drainage basin is evaluated as the contributing area. If the discharge volume is greater than that which can be attributed to infiltration within the drainage basin, then structural geological influences such as faults or fractures are considered. Although few faults have been mapped in the watershed west of the Mt. Bonnell Fault, small-scale faults with offsets on the order of less than one foot are identifiable. These faults represent zones of weakness and may act as ground water conduits within localized, shallow ground water systems or may permit ground water flow to occur between otherwise isolated ground water lenses.

2.2.2 Edwards Group And The Recharge Zone

The Edwards and Associated Limestones form the Edwards Aquifer, the single most important ground water resource in the Austin area. The Barton Springs Edwards Aquifer (BSEA) consists of the Georgetown Formation and Edwards Group (Rose, 1972, Senger and Kreitler, 1984, and Slagle and others, 1986). The BSEA can be divided into two geographic components: the Recharge Zone (RZ) - defined as the surface outcrop of the Georgetown and Edwards limestones where water directly enters the aquifer, and the Contributing Zone (CZ)- the area up gradient (upstream) of the RZ generally underlain by the Glen Rose Formation where most of the water recharging the aquifer originates (Santos, Loomis and Associates, 1995). The RZ for the BSEA covers an area of approximately 90 sq. mi. The watersheds of Barton, Slaughter, Williamson, Bear, Little Bear, and Onion Creeks comprise the CZ for the BSEA, covering an area of approximately 264 sq. mi.

The lowest portion of Barton Creek flows across the Recharge Zone of the Barton Springs segment of the Edwards Aquifer (BSEA). Recent studies have estimated that 31 percent of the water discharging from Barton Springs originates in the Barton Creek Watershed (Barrett and Charbeneau, 1996). Andrews and others (1984) estimated 28 percent for Barton Creek. This recharge relationship establishes a very important direct connection between Barton Creek and the Edwards Aquifer, in particular the northern-most extent of the BSEA as well as to Barton Springs. As such, a discussion of ground water in the Barton Creek Watershed would be incomplete without including the Edwards.

The primary focus for ground water investigations in the Barton Creek Watershed Study has been the springs discharging into Barton Creek and its tributaries. Sections 2.4 and 2.5 will discuss results of COA studies and data from Barton, Old Mill, Eliza, Backdoor, and Cold Springs. A general discussion of Edwards Aquifer water chemistry will be included (Section 2.6) to provide context for chemistry of BSEA springs and possible impacts from urbanization.

Spring discharges from the BSEA are important to the City of Austin for several reasons. Barton and its associated springs, Old Mill (also known as Sunken Gardens or Walsh Spring) and Eliza (also known as Concession, or Polio Pit) and Cold Springs (also known as Deep Eddy), discharge into Town Lake upstream of the Green Water Treatment Plant and, therefore, contribute to COA drinking water supplies. Backdoor Spring supplies water to a perennial pool over the Recharge Zone on Barton Creek and is an important water source for wildlife. The location of these springs are shown in Plate 1. The pool built around Barton Springs (see Appendix B, photo 1b) is a major attraction for the City and a revenue source for the Parks and Recreation Department. The Barton Springs salamander (*Eurycea sosorum*) inhabits the four springs (Barton, Old Mill, Eliza, and Upper Barton Springs) and has been petitioned for listing as an endangered species (Chippindale et. al, 1993) and in April 1997 the United States Fish and Wildlife Service (USFWS) listed the species as endangered.

The Edwards Aquifer is a karst aquifer. Porosity in the Edwards includes matrix porosity, generally intergranular voids of primary or secondary origin responsible for diffuse flow, and conduit porosity, secondary macroscopic voids associated with bedding surfaces, fracture planes, and fossil molds responsible for conduit flow. These voids occur in both the epikarst or unsaturated zone and the phreatic or saturated zone. Dissolution by recharging waters has progressively enlarged openings in the limestone and dolomite host rock creating an integrated network of conduits allowing rapid recharge from surface water and rapid ground water movement. Recharge waters enter the aquifer through point features such as caves or solution-enlarged fractures (see Appendix B, photo 1a) or as diffuse recharge through upland soils and bed rock surfaces. These waters pass through the epikarst to the phreatic zone. Water may be present in perched horizons within the epikarst and epikarst conduits may temporarily flood during recharge events. Springs dominated by diffuse flow may be characterized by relatively constant discharge and stable water chemistry. Spring recharge areas dominated by diffuse recharge may have similar characteristics. Springs dominated by conduit flow may be characterized by highly variable or flashy discharge and variable water chemistry. Spring recharge areas dominated by point recharge may have similar characteristics.

Numerous investigators have studied the BSEA. Papers by Adkins (1933), Rodda and others (1966), Fisher and Rodda (1969), and Rose (1972) provide the framework for Edwards stratigraphy. Mapping by Rodda and others (1970) and Garner and Young (1976) are the most commonly used geologic maps of the Austin area. Detailed hydrogeologic and water chemistry studies by the USGS (Andrews et. al., 1984; Slade et. al., 1986) and the Bureau of Economic Geology (Senger and Kreitler, 1984) and the Texas Water Development Board (Baker and others, 1986) have provided the basis of understanding recharge and chemical composition of the aquifer. A recent study by the BS/EACD (Hauwert and Vickers, 1994) documented several specific occurrences of water quality degradation within the aquifer and defined a probable major flow path in the vicinity of Sunset Valley leading toward Barton Springs. Several University of Texas graduate theses have focused on the Edwards, including most recently Abbott (1973), Browning (1977), Smith (1978), St. Clair (1979), Kolb (1981), Kastning (1983), Senger (1983), Clement (1989), Alexander, (1990), Parten (1991), Oetting (1995), Mahler (1997), and Remington (in preparation).

2.2.3 Terrace/Alluvial Local Ground Water Systems

Terrace deposits and alluvial deposits are found along the entire course of Barton Creek. These deposits accumulated during the Pleistocene period and the Holocene period (Garner and Young, 1976). Gravel, sand, and some silt comprise the deposits. Thickness varies but it is typically less than 30 feet. The material is derived by mechanical weathering of primarily the Glen Rose Formation, with some debris of the Edwards Group and the Walnut Formation. Thick accumulation of terrace deposits occurs in the downstream portion of Barton Creek, particularly near confluences with large tributaries. An example of this is the large, flat area where Lost Creek Country Club is located near the confluence of Short Spring Branch and Barton Creek. In other locations, terrace deposits tend to accumulate on the inside portion of meander loops of Barton Creek.

Rain water infiltration, ground water, and possibly overbank flow of Barton Creek water, accumulate within the gravel deposits to form local, shallow ground water systems. Springs are found discharging from several terrace deposits along Barton Creek, particularly in the downstream portion of the Contributing Zone. Additional terrace springs are located in areas where DUD staff have not been able to collect samples. At most locations, sample collection is impeded by low discharge volume, or the discharge does not occur at a discrete point. Springs are typically recognized by the presence of travertine deposits, maidenhair fern, and spike rush.

2.3 CHARACTERISTICS OF GROUND WATER DISCHARGE TO BARTON CREEK

Approximately 112 square miles or 94 percent of the Barton Creek Watershed is within the Contributing Zone to the Barton Springs segment of the Edwards Aquifer (Santos, Loomis and Associates, 1995). The Glen Rose Formation is the predominant geologic unit in the Contributing Zone (Barnes, 1974, 1981). Rainwater which infiltrates the soil and rock recharges local, shallow ground water systems within the limestone of the Glen Rose Formation or within alluvial deposits associated with Barton Creek and its tributaries. Ground water from these local, shallow ground water systems slowly discharges into the creeks, providing the clear clean baseflow common in the Hill Country. Over the Recharge Zone, baseflow enters fractures, faults, sinkholes, and solution openings within the creek bed and into the BSEA.

During periods of normal rainfall, there is usually baseflow in Barton Creek throughout the Contributing Zone. Baseflow continues as long as there is shallow ground water. During recent drought conditions of Winter 1995 through Summer 1996, surface flow in the Contributing Zone occurred only in isolated sites. Very slow underground flow, or underflow, was occurring beneath gravel bars within Barton Creek but was not visible on the surface except as pools.

Factors which affect the amount of baseflow in Barton Creek include:

- amount and location of rainfall in the watershed
- rate of rainfall (intensity of storm)
- antecedent moisture conditions in the soils
- capacity of the soils and rock to absorb and release water
- topography and soil thickness in the area of infiltration
- land surface available for infiltration of rainwater
- rate of evapotranspiration
- vegetative cover interception of rainfall
- interception of ground water supplies via water wells or irrigation practices.

Marsh and Marsh (1993) reported that measurements of flow in Barton Creek at Hwy 71 during a period of high precipitation (October 1, 1991 to April 30, 1992) revealed that 48 percent of rainfall was converted to stream discharge. This was an exceptionally wet winter, with over 14 inches of rain in December. During an earlier period of high precipitation (October 1, 1990 to September 30, 1991), only 12 percent of rainfall was converted to stream discharge. The difference in the volume of rainfall contributing to baseflow was attributed to different antecedent moisture conditions, dictated by rainfall amounts. Scant rainfall preceded the earlier period of measurement, creating conditions favorable for greater ground water storage. Saturated conditions within the soils and perched water zones lead to runoff of a larger proportion of rainfall during the winter of 1991 and spring of 1992. A more detailed presentation of runoff and baseflow coefficients for Barton Creek can be found in the Barton Creek Watershed Model Report (COA, 1997).

2.3.1 Tributary Flow Characteristics

In an effort to understand physical and chemical conditions in waterways, COA staff began monitoring of 14 watersheds to collect data on flow rates and water chemistry. Because these tributaries are relatively ephemeral, spring-fed streams, their flow behavior is addressed as symptomatic of ground water hydrology rather than surface water. These watersheds were selected to represent a variety of land uses with different methods of wastewater disposal. Land uses include predominantly rural (no homes or scattered homes on large lots, assumed impervious cover <10 percent), low density residential (many homes, varying lots sizes, assumed impervious cover <25 percent) with on-site wastewater disposal (septic systems), and moderate density residential (many homes on small lots, assumed impervious cover <40 percent) with central wastewater collection (including one with local wastewater irrigation from a package treatment plant). Five of the fourteen watersheds are in the Barton Creek drainage basin and several others are in adjacent watersheds. This data set overlaps that analyzed in Section 3.2 in the Canyon Study. All sites are on the west side of Austin and should have similar soil characteristics. Analysis of flow in these watersheds has provided information on baseflow characteristics in these settings, different responses of selected watersheds to rain events, upland rain infiltration, and shallow ground water discharge to drainage systems.

Data discussed here include the first five flow measurements. These include measurements taken one day following a rain event, weekly measurements for three weeks, and then measurements four weeks later. Field work was initiated June 1, 1995 following several days of heavy rain and a relatively wet winter of 1994 and spring of 1995. The first day's measurements were taken between nine and 17 hours following 0.4 to 1.1 inches of rain, depending on location. A total of 4.7 to 8.3 inches of rain fell during the previous five days.

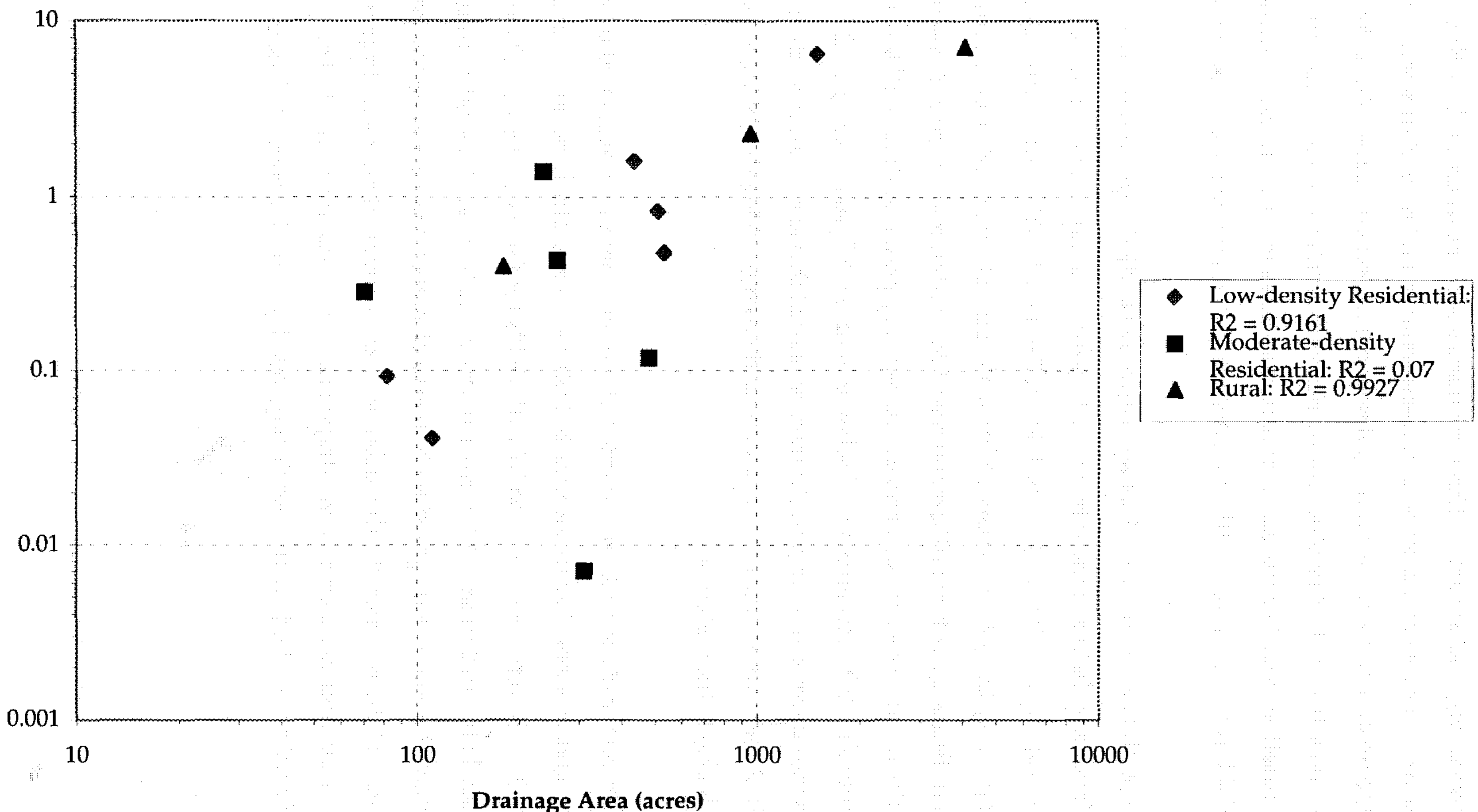
Initial discharge measurements and yield calculations were high but rapidly declined. Eight of the fourteen tributaries were dry by late July. Two of the remaining six tributaries with flow were in the two largest watersheds with rural or low density housing served by on-site wastewater disposal systems. Three tributaries were in watersheds with moderate density residential housing served by central wastewater collection and treatment provided by either package treatment plants or municipal regional treatment plants. These three tributaries appear to have baseflow well after other tributaries with similar watershed size were dry. The source of the baseflow could be varied - infrastructure leaks in either water or wastewater systems, plentiful lawn irrigation, or effluent irrigation potentially in the case of one tributary.

Bivarient plots were made of drainage basin size to discharge volume to determine the nature of the relationship between these two variables for each day of discharge. An example of this relationship is provided for June 8, 1995 in Figure 2.1. Tributaries with rural or low density housing on septic systems consistently displayed a strong positive correlation between basin size and discharge volume (R^2 greater than 0.9). Tributaries on central wastewater collection, generally urban areas, consistently displayed very poor correlation (R^2 less than 0.1). The lack of relationship between area and discharge in urban tributaries can possibly be attributed to impervious cover preventing infiltration of rainfall therefore upsetting the natural hydrologic cycle in these watersheds and/or unnatural discharges (illegal discharges, water or sanitary sewer leaks) to the waterways.

Yield for each watershed from the point of measurement was calculated by dividing flow as gpm by area as acres. Yields for June 8, 1995 were generally between 0.1 and 2.0 gpm/acre (Figure 2.2). Seven weeks later on July 20, yields for the 6 tributaries still running were generally between 0.01 and 0.1 gpm/acre (Figure 2.3). One of the urbanized tributaries that maintained baseflow is irrigated with treated effluent from a package treatment plant in the upper end of the watershed. This tributary has maintained relatively high water yields, consistently around 0.1 gpm/acre, despite nearly record low rainfall. This yield is well above that of rural watersheds with flow during this dry period (about 0.005 gpm/acre).

Figure 2.1

Tributary Flow/Area Relationship
June 8, 1995



Source: COA/DUD Database

2.3.2 Mainstem Baseflow Characteristics

Bivariate plots of discharge and drainage area for Barton Creek pool monitoring sites (see Section 3.2) do not show the high degree of correlation seen in the tributary systems. This may result from pool site selection which was designed to focus on water quality and biology of the pools rather than hydrology. Most of the pool sites are not ideal for measuring discharge, particularly under low flow conditions, because of large amounts of alluvium in the channels (see Appendix A for pool descriptions and photographs). In fact, under low flow conditions, measured discharge sometimes decreases downstream (Figure 2.4). These sites are generally those where large alluvial gravel bars partly obstruct the channel, such as Pool 6. At these sites, a significant amount of water is more likely to move through the gravel bars than through the existing channel. This phenomenon is likely to occur at other sites such as Pool 3 and 5, but the flow losses through the gravel may be masked by the large increases in drainage area upstream.

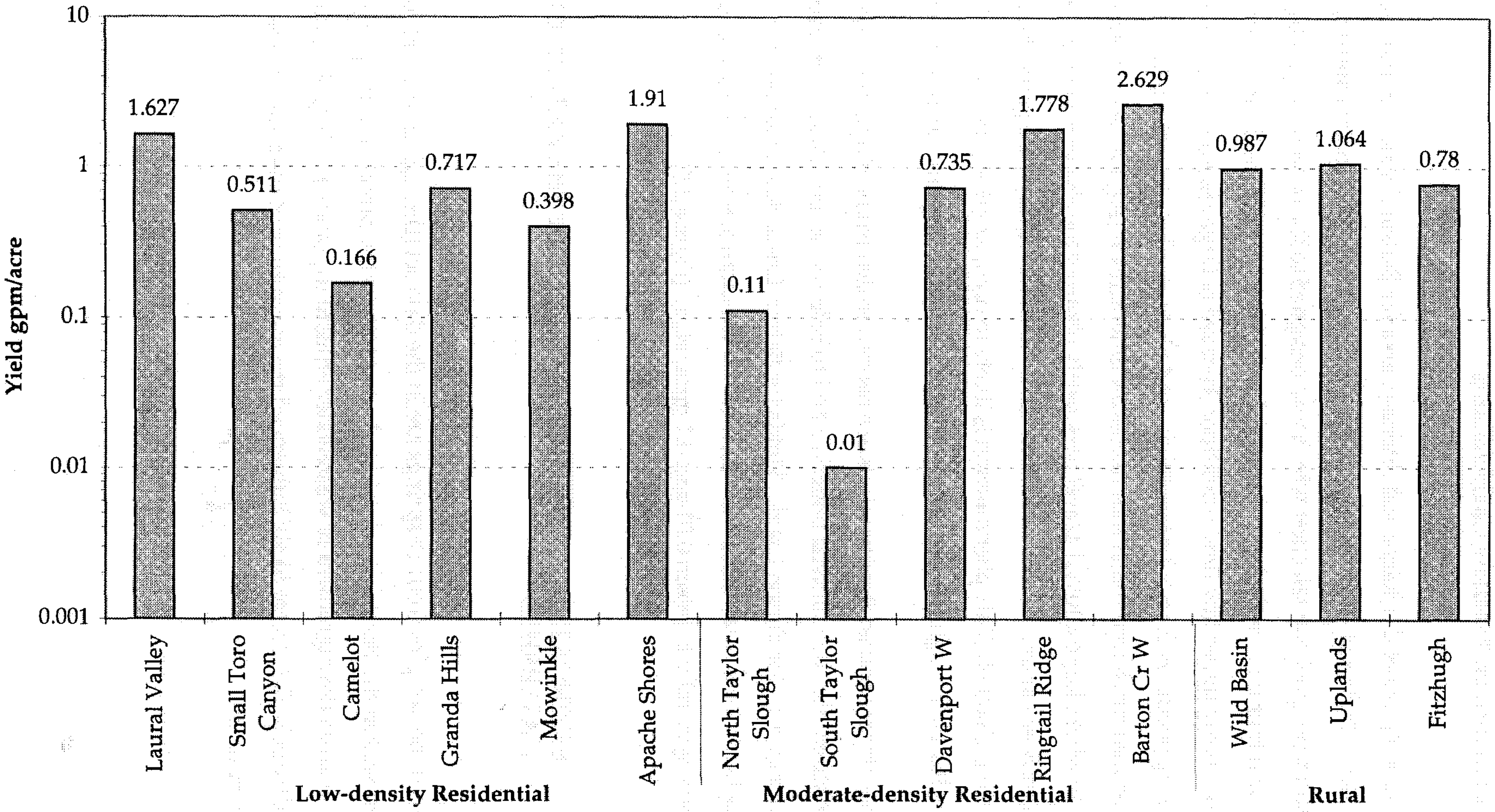
More closely spaced flow transects are needed to determine if apparent flow losses are due to movement through alluvial materials and to help refine the relationship between discharge and drainage area for Barton Creek. Yields for Barton Creek flows measured in August 1995, a couple of weeks after those measured on the tributaries, were in the same range as tributary yields, generally between 0.01 and 0.1 gpm/acre. (Figure 2.5)

2.4 SPRINGS IN THE CONTRIBUTING ZONE OF THE BARTON CREEK WATERSHED

Forty-nine samples from 12 springs are in the data set (through mid-1996) for the Contributing Zone within the Barton Creek Watershed. Many of the samples from springs in urban settings are in areas downgradient of wastewater effluent irrigation fields (golf courses or native landscape). This factor likely influenced the magnitude of chemical differences between urban and rural sites.

Figure 2.2

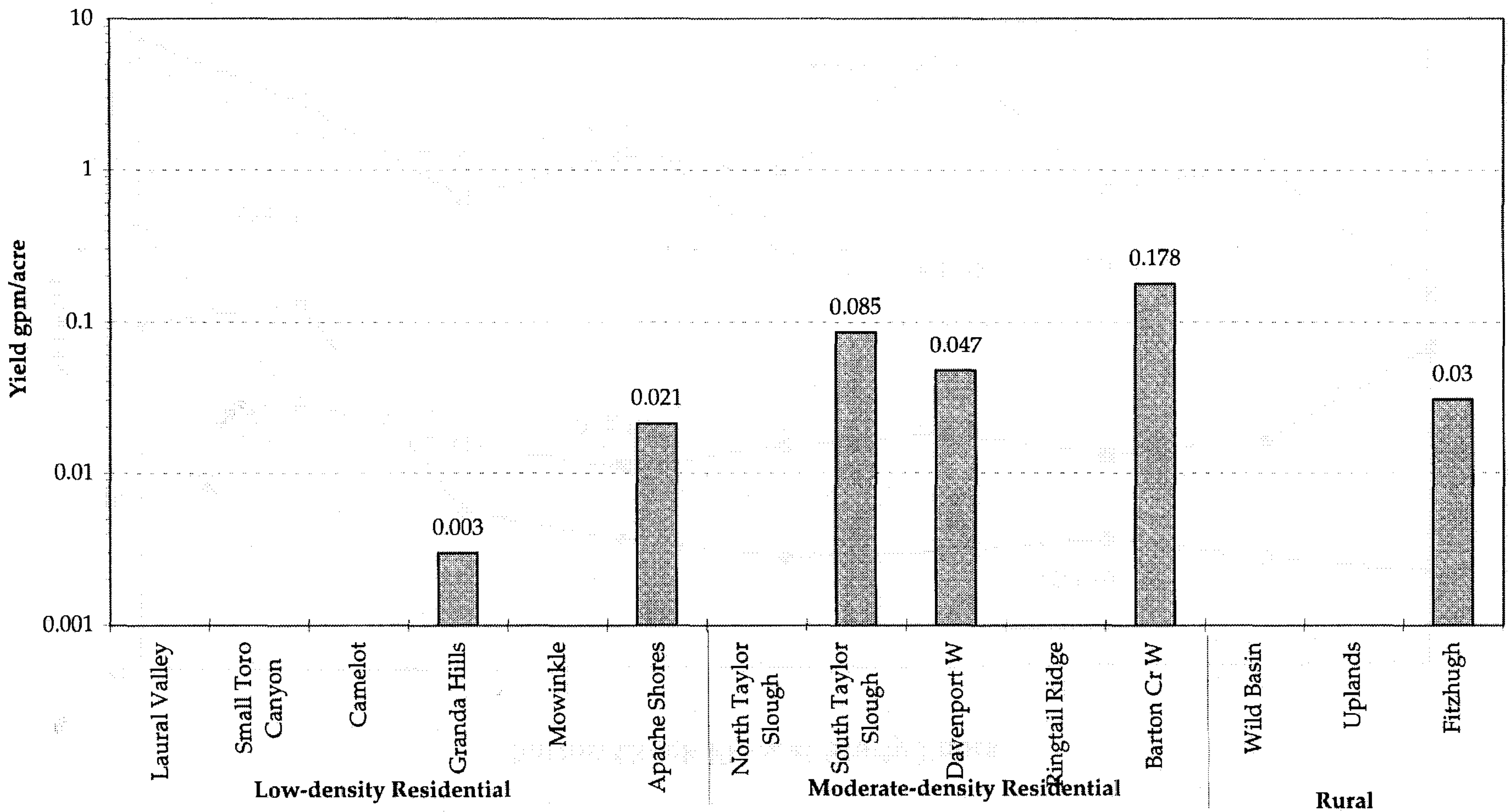
Tributary Water Yields
June 8, 1995



Source: COA/DUD Database

Figure 2.3

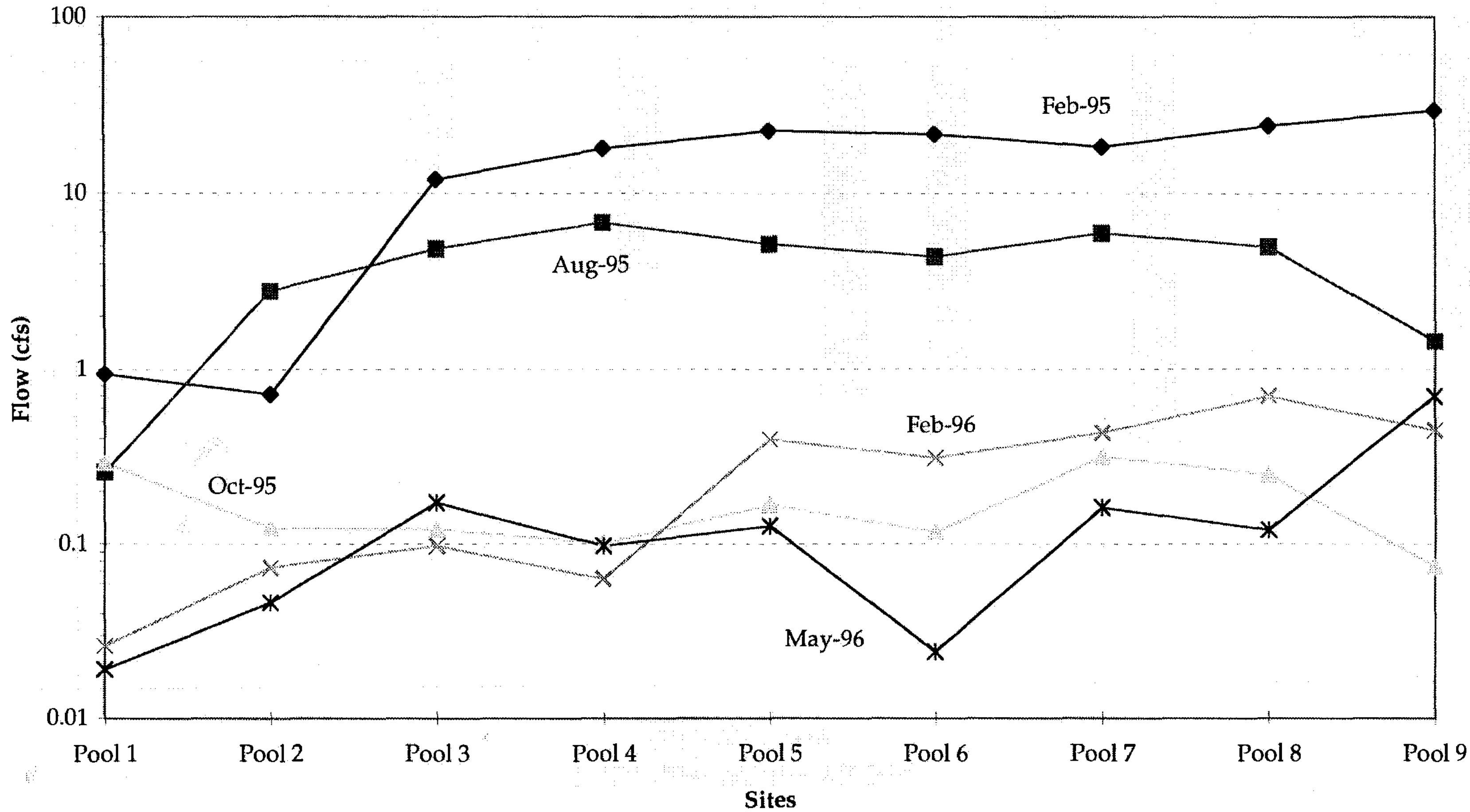
Tributary Water Yields
July 20, 1995



Source: COA/DUD Database

Figure 2.4

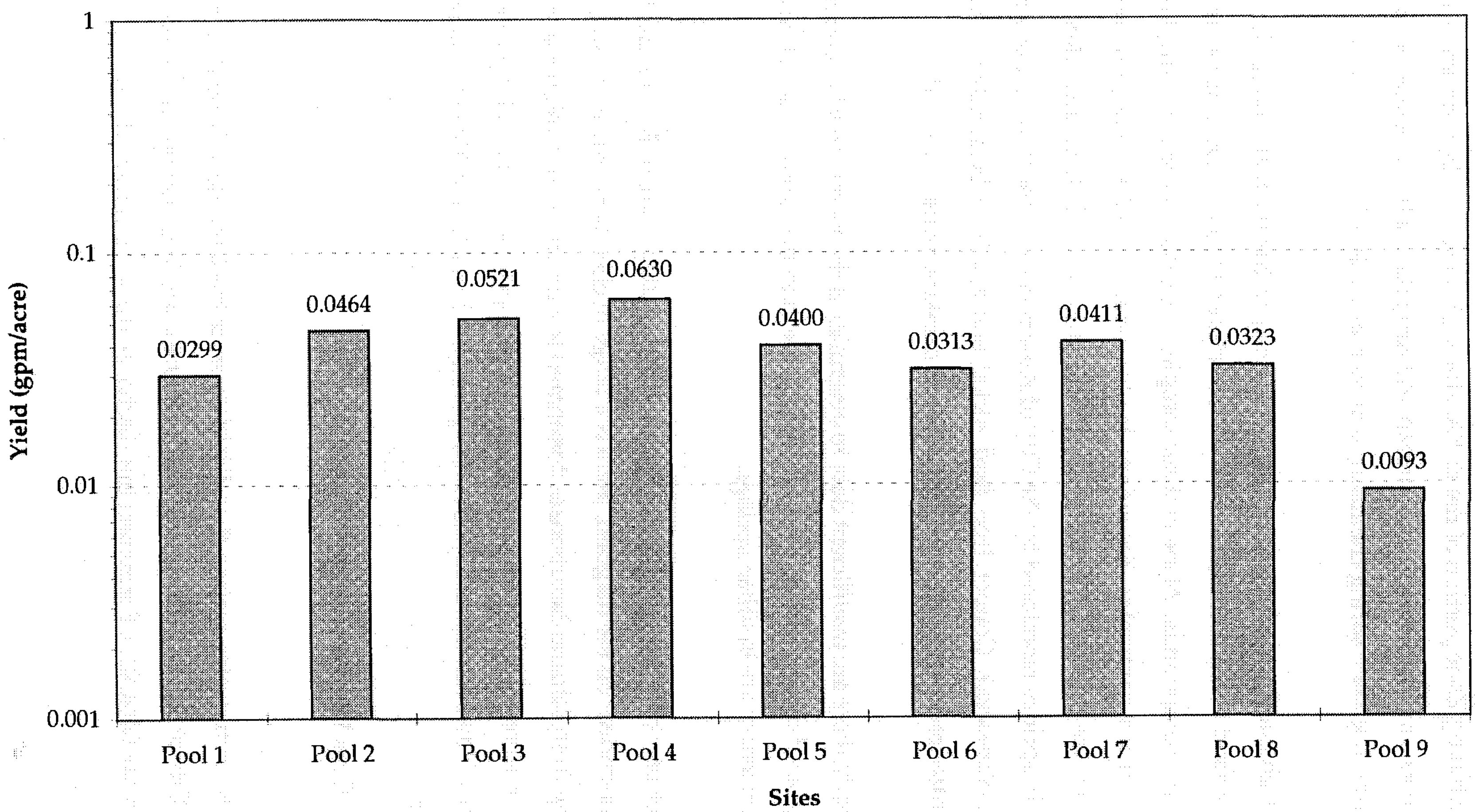
Barton Creek Flow at Study Pools



Source: COA/DUD Database

Figure 2.5

Barton Creek Water Yields
August 1995



Source: COA/DUD Datebase

In general, ground water quality is good in springs in the Barton Creek Watershed in the Contributing Zone portion of the BSEA, although localized degradation is evident based on differences in water chemistry in urban and rural data sets. A summary of Barton Creek Contributing Zone spring chemistry is shown in Table 2.3.

Although many samples were analyzed for only nutrients, many were also tested for major ions and selected heavy metals, and two were analyzed for a comprehensive suite of organic and inorganic compounds. None of these samples exceeded the primary drinking water standards MCLs for any parameter. Secondary drinking water standards have not been exceeded by any samples (See Appendix E). No synthetic organic chemicals have been detected during this study in springs monitored by the City of Austin in the Contributing Zone portion of the Barton Creek Watershed. Copper, iron, lead, nickel, and zinc have been detected at seven sites at concentrations well below State and Federal drinking water standards.

Currently there are insufficient data to determine if the heavy metal occurrences exceed background concentrations because of variable detection limits and lack of data, although 10 of 13 occurrences are in urban springs.

A Piper plot of all sampled springs in the Contributing Zone of Barton Creek is shown in Figure 2.6. As evident on the diagram, there is a range of chemistry expressed in these springs, ranging from calcium-bicarbonate dominated to calcium-mixed anion waters. Based on this diagram alone, there is little distinction between springs in rural settings and those in urban settings. However, this analysis is hampered by the lack of sufficient data from springs in rural settings.

2.4.1 Glen Rose Formation

Samples from twelve springs that discharge from the Glen Rose Formation have been collected by the City of Austin (Plate 1). In addition, there are four springs that apparently have recharge areas in the Glen Rose Formation but discharge through Terrace deposits.

Piper diagrams have been prepared from spring chemistry data collected by ERM staff. Figure 2.7 is a Piper diagram of the major cation and anion concentrations of six ground water samples collected from Glen Rose Formation springs. The relative proportions of the cations calcium, magnesium, and sodium to anions carbonate, sulfate, and chloride are used to classify the type of ground water. This figure shows considerable spread between rural and urban spring samples. The ground water is classified as calcium-carbonate water because the dominant constituent ions are calcium and carbonate. This classification is common in limestone terrain aquifers.

2.4.2 Terrace/Alluvial Deposits

Six springs that issue from terrace or alluvial deposits adjacent to Barton Creek are regularly monitored by the DUD. These springs, shown on Plate 1, are primarily located in the downstream reaches of Barton Creek and are generally classified as calcium-carbonate to calcium-mixed anion water. Figure 2.8 is a Piper diagram displaying the major cation and anion concentrations of ground water samples collected from terrace/alluvial deposit springs. The localized occurrence of Barton Creek terrace deposits suggests that the ground water in them is locally derived from infiltration of surface water (rain, irrigation, or overbank storage) or possibly from buried Glen Rose springs. Therefore, variations in the chemical signature of the terrace/alluvial deposit springs most likely result from local impacts or possibly the variegated nature of the lithologic material within the deposits.

2.4.3 Comparisons Of Ground Water Chemistry At Urban vs. Rural Sites

Potential ground water chemistry impacts that are due to anthropogenic influences have been investigated by comparison of parameter concentrations. Because of the relatively small size of the available data set, interpretation has been limited to graphical comparison and statistical Analysis of Variance (ANOVA) tests. See Table 2.3 for sample sizes for each parameter. Statistical evaluation indicates a relationship between urbanization and changes in ground water chemistry.

Table 2.3
Summary of Barton Creek Contributing Zone Spring Chemistry

SITE	pH	TDS	TEMP	SpCond	TURB	DIS OXYGEN	NH3-N	ORTHO P	NO3-N	TKN	TP	FECAL C	FECAL S	∂15Nair
		mg/L	C	us/cm	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	colonies/100ml	colonies/100ml	
4/92-9/96														
Urban														
Average	7.28	447	21.6	1128	2	5.20	0.02	0.027	1.61	0.24	0.02	6	21	10.26
Median	7.36	455	21.8	1090	1	5.31	0.01	0.02	1.3	0.25	0.01	1	18	5.3
Max	7.7	749	27	1660	14	6.8	0.2	0.26	5	0.45	0.08	25	38	29.45
Min	6.7	230	16.8	818	0	3.5	0	0	0.11	0.12	0.005	0	10	1
Count	38	33	30	16	17	3	40	43	43	15	14	11	4	9
Non-detections							15 ND	15 ND		3 ND	11 ND	4 ND		
Rural														
Average	7.43	281	20.2	560	1	4.49	0.02	0.03	0.33	0.16	0.015	4	14	8.57
Median	7.4	300.5	20.8	608	1	4.49	0.01	0.02	0.17	0.16	0.01	4	14	5.25
Max	8.3	560	26	618	3	4.5	0.07	0.13	1.24	0.27	0.03	7	28	21.5
Min	6.9	150	7	455	0	4.48	0	0.01	0.04	0.055	0.01	0.5	0.5	-1.05
Count	13	12	12	3	6	2	13	15	14	4	4	4	2	3
Non-detections							4 ND	3 ND	3 ND	2 ND	3 ND	1 ND		

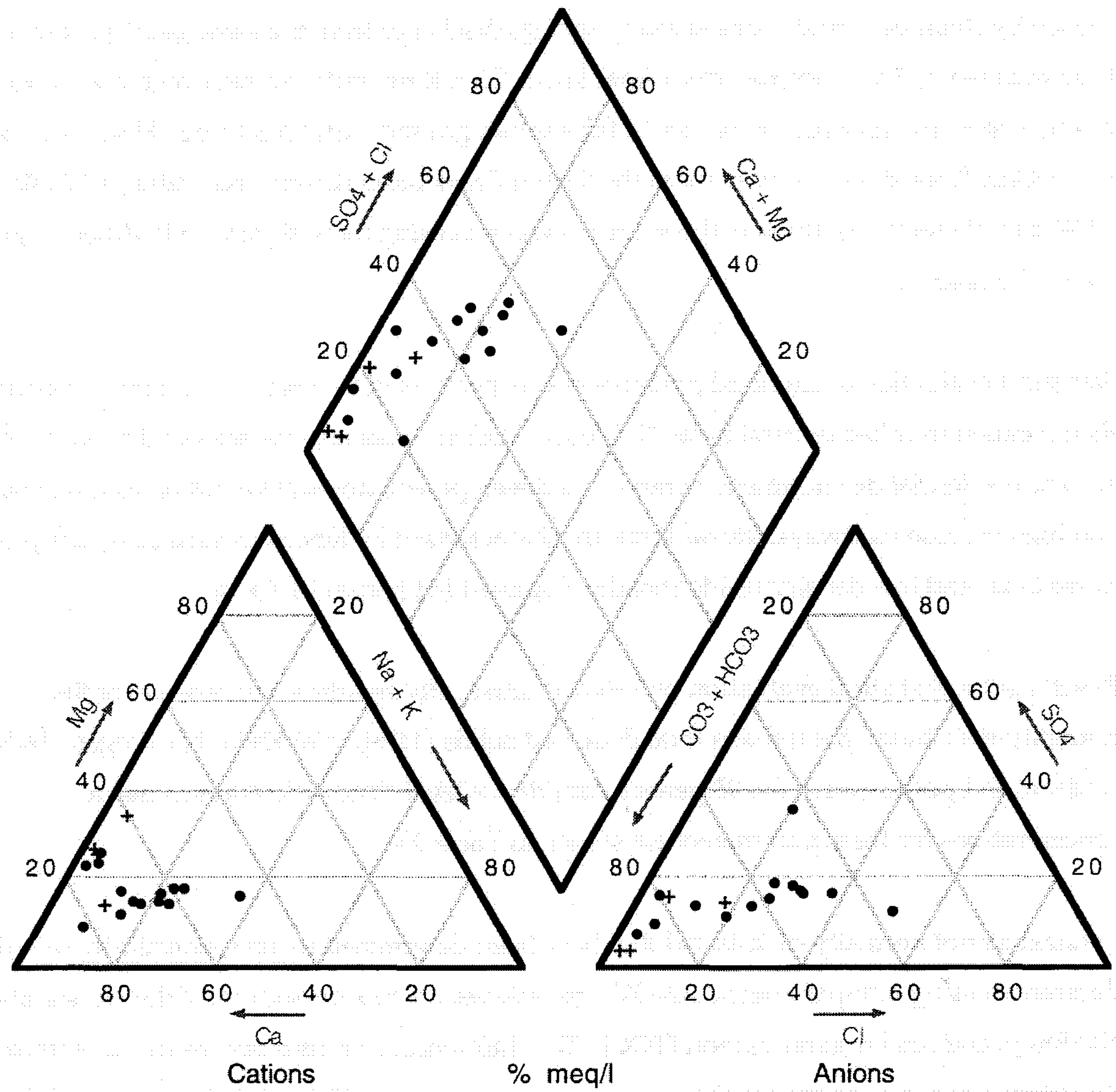
SITE	FL	Na	Mg	Ca	Cl	SO4	K	ALKALINITY	TOC	Sb	As	Ba	Be	Cd
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L
4/92-9/96														
Urban														
Average	0.18	42.86	19.7	130.3	95.09	75.61	3.11	324	9.00			0.032		
Median	0.15	42.9	19.2	129.5	89.40	67.2	2.89	320	1.97			0.032		
Max	0.44	120	27.4	155	266	220	6.55	446	74.8	0	0	0.037	0	0
Min	0.08	5.96	10	109	14	27	0.5	253	1.06	0	0	0.027	0	0
Count	15	15	14	14	13	13	10	15	11	0	0	2	0	0
Non-detections							1 ND			2ND	12ND		2ND	2ND
Rural														
Average	0.17	7.86	18.1	85.9	15.55	26.24	0.69	260	1.71					
Median	0.16	5.97	18.2	86.8	10.65	23.63	0.69	245	1.71					
Max	0.27	16.4	25.5	116	36.4	50.6	0.85	320	1.71	0	0	0	0	0
Min	0.09	3.12	10.5	54.2	4.48	7.1	0.52	231	1.71	0	0	0	0	0
Count	4	4	4	4	4	4	2	4	1	0	0	0	0	0
Non-detections							2ND		2ND		3ND			

SITE	Cr	Cu	Fe	Pb	Mn	Hg	Mo	Ni	Se	Ag	Sr	Tl	Zn	
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	
4/92-9/96														
Urban														
Average		0.009	0.006					0.003			0.4665		114	
Median		0.009	0.006					0.003			0.4665		114	
Max	0	0.011	0.008	0	0	0	0	0.003	0	0	0.545	0	146	
Min	0	0.006	0.005	0	0	0	0	0.003	0	0	0.388	0	86	
Count	0	2	5	0	0	0	0	1	0	0	2	0	2	
Non-detections	2ND	10ND	5ND	12ND	2ND	2ND	2ND	7ND	2ND	2ND		2ND	2ND	
Rural														
Average			0.05	0.003									121	
Median			0.05	0.003									121	
Max	0	0	0.05	0.003	0	0	0	0	0	0	0	0	121	
Min	0	0	0.05	0.003	0	0	0	0	0	0	0	0	121	
Count	0	0	1	1	0	0	0	0	0	0	0	0	1	
Non-detections		3ND	2ND	2ND				1ND						

Source: COA/DUD Database, 1992-96

Figure 2.6

Barton Creek Contributing Zone Urban and Rural Springs Ion Data



Rural sites are indicated by plus signs (+) and urban sites are indicated by filled circles (•).

Source: COA/DUD Database 1992-1996.

The relationship between urbanization and ground water chemistry does not appear to be caused by changes in host rocks as many springs discharge from the same geologic unit, Glen Rose member 3. For example, water from lower Glen Rose units can have high concentrations of some constituents which may yield a false urban ground water signature. However, the lower Glen Rose does not crop out in the Barton Creek basin (Brune and Duffin, 1983; Barnes, 1974) and, therefore, is unlikely the source of water causing these significantly different ground water chemistries.

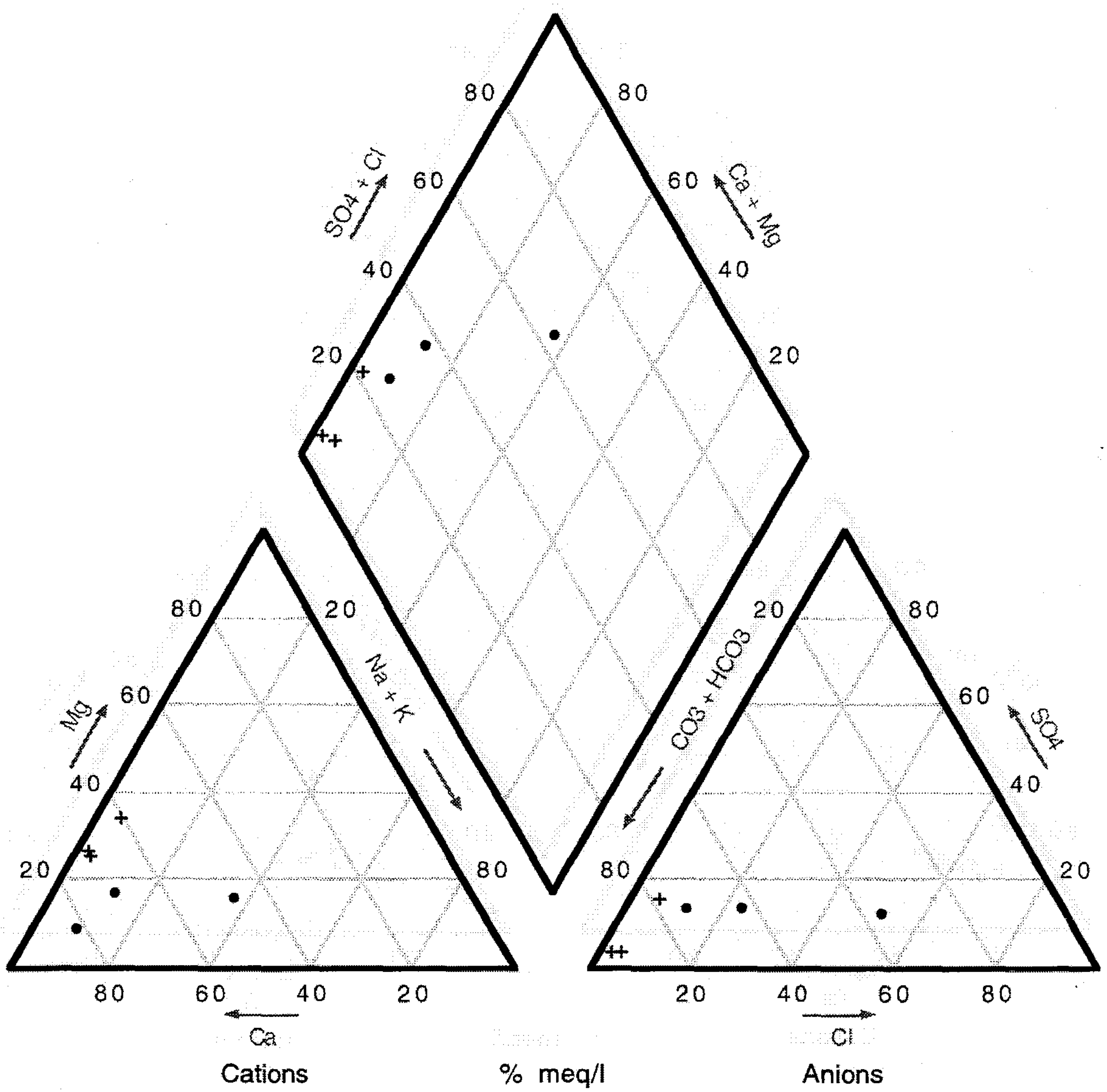
Statistical evaluation of chemical parameters was performed for springs grouped according to their location in urban or rural areas (Table 2.2). Urban areas are characterized by land uses such as residential development, commercial development, non-native turf areas (golf courses), and high volume roadways. Rural areas are characterized by land uses such as nature preserve, range land, and low density residential development (<1 home/10 acres).

Results of the statistical evaluation revealed a statistically significant difference for the normally-distributed parameters total dissolved solids (TDS), total Kjeldahl nitrogen (TKN), calcium, and potassium at the 95 percent confidence level. The differences in mean concentrations for these parameters are shown in Table 2.4.

Parameters not normally-distributed that have been determined to have statistically significant differences using non-parametric ANOVA techniques are nitrate, sodium, chloride, sulfate, alkalinity, and total organic carbon (TOC). The differences in arithmetic mean concentrations of the urban and rural groups for these parameters are shown in Table 2.4. Using ranked data censored at the highest detection limit, the results in Tale 2.4 remained essentially the same with the exception of TKN. For this parameter the alternate treatment of non-detect would conclude that no significant difference occurs; however, the variable detection limit with a single high outlier limit makes this treatment less reliable than substitution at the half detection limit level.

Figure 2.7

Barton Creek Glen Rose Formation Urban and Rural Springs Ion Data

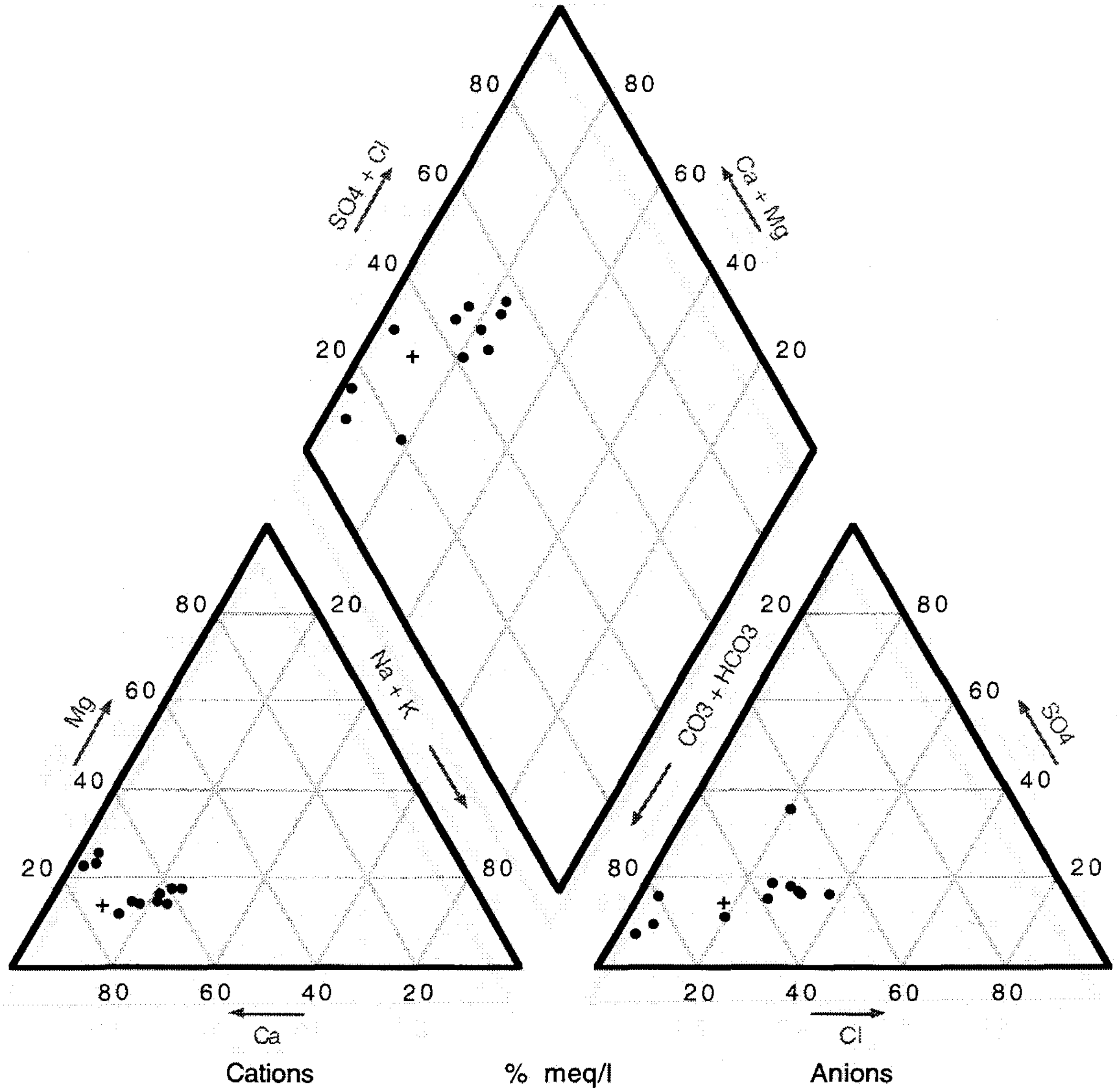


Rural sites are indicated by plus signs (+) and urban sites are indicated by filled circles (•).

Source: COA/DUD Database 1992-1996.

Figure 2.8

Barton Creek Terrace Urban And Rural Springs Ion Data



Rural sites are indicated by plus signs (+) and urban sites are indicated by filled circles (•).

Source: COA/DUD Database 1992-1996.

Table 2.4 Results of Statistical Evaluation of Contributing Zone Springs

	Urban mg/L	**Rural mg/L**
Normal Distribution		
TDS	449.91	280.92
TKN	0.24	0.16
Calcium	130.29	85.93
Potassium	3.39	0.62
Non-Normal Distribution		
Nitrate-N	1.65	0.34
Sodium	50.03	7.86
Chloride	91.27	15.55
Sulfate	70.2	26.2
Alkalinity	323	260
TOC	12.8	1.71

2.4.3.1 Total Dissolved Solids

TDS is the sum of the mass of the ions plus silica and other organic and inorganic constituents. This measurement provides a means of determining the relative mineral content of ground water. It is also an indicator of salinity and suitability for drinking water. TDS values in this section are from field probes which use conductivity values multiplied by a conversion factor to estimate TDS.

TDS concentrations ranged from 150 milligrams per liter (mg/L) to 749 mg/L (Table 2.3). TDS concentrations less than 250 mg/L were measured at six spring locations, one of which was an urban site. Concentrations greater than 500 mg/L were measured at ten spring locations, one of which was a rural site. This rural spring is classified as such because of the dominant local land use. However, a major road passes directly over the spring and runoff or fill in the bridge approach may be affecting the water chemistry.

Possible explanations for higher TDS concentrations in urban springs include:

- Water, rain water and/or irrigation water, infiltrating through turf grasses leaching greater amounts of minerals, salts, and nutrients.

- Roadway runoff containing high concentrations of minerals and metals is a major component of recharge water.

- On large managed turf grass areas (golf courses) percolation of water (rain or irrigation) results in the transport of dissolved constituents (pesticide compounds, nutrients, and salts) which have accumulated in the soil or are present in irrigation water, to the ground water system.

- Leachate from septic tanks or leaking wastewater lines introduces dissolved constituents into ground water which can influence spring TDS.

2.4.3.2 Nutrients

TKN is defined as organically bound nitrogen. Laboratory determined concentrations of TKN are organic nitrogen plus ammonia nitrogen. Organic nitrogen from natural sources includes proteins, peptides, nucleic acids and urea. A common manmade source of organic nitrogen is sewage. TKN concentrations ranged from less than 0.1 to 0.45 mg/L (Table 2.3)

Nitrate-nitrogen concentrations in urban springs were significantly higher than in rural springs with means of 1.61 mg/L and 0.33 mg/L respectively (Table 2.3). Ranges in concentrations also reflect this trend with a range of 0.11 to 5.0 mg/L for urban springs compared to a range of 0.04 to 1.24 mg/L in rural ground water. Possible explanations for higher nitrogen concentrations in urban springs include:

- On soils managed for turf grass with fertilizers, deep percolation of water (rain or irrigation) may result in the transport of nitrates accumulated in the soil to the ground water.

- At golf courses managed with fertilizers and irrigated with wastewater effluent, runoff that infiltrates to ground water may have elevated nitrate concentrations.

- Leachate from septic tanks or leaking wastewater lines may introduce high nitrate concentration into the ground water.

- Roadway runoff with elevated nitrate concentrations is a major component of recharge water.

Coincident high nitrate-nitrogen concentrations have been measured in springs at Site 55 and Site 72/73 (Sites 72 and 73 are different discharge points of the same spring). The nitrate-nitrogen concentrations at Site 55 have ranged from 0.8 to 2.8 mg/L. The nitrate-nitrogen concentrations at Site 72/73 (see Appendix B, photo 2b) have ranged from 0.6 to 5.0 mg/L. Surface water chemical analyses indicate that elevated nitrate concentrations also occur in pools downstream of these spring locations (see Section 3.0) particularly during very low creek flow conditions, as seen during the recent drought. The nitrate concentrations measured at the pool downstream of Site 72/73 (0.15 mg/L median concentration) are consistently higher than in any of the other monitored pools of Barton Creek.

A potential source of the elevated nitrate in ground water at the Sites 55 and 72/73 is wastewater effluent irrigation and the use of nitrogen fertilizer at golf courses upgradient from these springs. Several samples from each spring and potential nitrogen sources were analyzed for nitrate concentrations and nitrogen isotope ratios. The results are provided in Table 2.5.

Nitrogen stable isotope ratios and nitrate concentrations in the effluent holding ponds are similar to those detected in the springs. It appears that the effluent holding ponds, or the effluent irrigation on the golf course, is the source of the high nitrate concentrations observed in the springs at Sites 72 and 73. It is possible that the elevated nitrate concentrations at Site 55 are also related to irrigation with effluent and the application of nitrogen fertilizers in the catchment area upslope of the spring. Insufficient data are available to conduct statistical analyses of the numerical relationships, but the available analytical data and absence of other high nitrogen sources supports this conclusion.

The potential source of nitrogen in effluent used for turfgrass irrigation is discussed in "Irrigation of Turfgrass with Wastewater" (Mancino and Pepper, 1994). This study found that nitrate was lost in leachate beyond the turf root system. The highest concentrations in leachate occurred in December, January, February, June, and July when nitrate concentrations were highest in the wastewater. Because high evapotranspiration rates occur in June and July, the author suggested that this resulted in higher concentrations of nitrate in the leachate. Slow turf growth in December, January, and February reduces the nitrogen uptake and probably results in higher concentrations passing through the soils into the ground water. These mechanisms may explain the elevated nitrate concentrations observed in Sites 55, 72, and 73.

Further indications that effluent irrigation leachate is affecting spring water quality at Sites 55, 72, and 73 include:

- Copper and iron were detected in samples (8/29/95) that also had elevated nitrate concentrations. Copper and iron are common constituents of effluent (Mancino and Pepper, 1994) and have not been commonly detected in unimpacted springs.

- The chloride concentrations in the 8/29/95 samples at Site 72 (60 mg/L) and at Site 55 (116 mg/L) are considered elevated in comparison to rural springs (15.6 mg/L). Chloride concentrations in effluent from City treatment plants range from 62 to 159 mg/L.

- Sodium to chloride ratios of eight spring samples were calculated. A plot of the ratios is shown in Figure 2.9. Ratios of 0.49 and 0.26 in 8/29/95 samples (Site 72 and Site 55) indicate a source of chloride in addition to the weathering of naturally occurring sodium-chloride rock materials. Figure 2.10, a bar plot of the sodium and chloride concentrations of the same samples, depicts the proportion of sodium to chloride.

Table 2.5. Nitrate-N And Nitrogen Isotope Analysis For Sites 55, 72, And 73

Site name	Date	Nitrate-N (mg/L)	del 15 N
Golf course holding pond	2/7/94	2.6	21
Site 72	2/22/94	2.4	22.1
Site 72	4/19/94	2.6	19
Site 73	4/19/94	2.5	12.9
Pool 8	2/24/94	---	8.5
Site 72	2/22/95	0.6	4.2
Golf course holding pond	2/13/96	4.3	22.4
Site 72	2/13/96	2.4	29.5
Pool above Site 55	2/15/94	---	4.6
Golf course holding pond	4/19/95	---	6.0
Site 55	2/15/94	---	6.1
Site 55	2/15/94	---	7.1
Site 55	2/22/95	1.0	5.1
Site 55	2/13/96	0.7	5.3
Rural spring mean (n=14,3)		1.61	8.57
Urban spring mean (n=43,9)		0.33	10.26

A recent study of ground water analyses in the Long Island, New York area identified statistically significant differences in constituent concentrations between developed, densely populated areas and undeveloped areas. Eckhardt and Stackelberg (1995) identified higher concentrations of nitrate (in addition to boron, alkalinity, synthetic solvents, and pesticides) in newly developed residential areas, residential areas more than twenty years old, and in agricultural land compared to forested (undeveloped) areas. During evaluation of the effect of land use on nitrate concentrations in ground water, the authors identified median concentrations of nitrate below four mg/L in undeveloped sites and median concentrations of five to nine mg/L in developed sites. The sources of nitrate identified for the study area include nitrogen fertilizers and sewage wastes.

Another possible source of elevated nitrate is atmospheric input of nitrogen from industrial sources. Dry deposition (dust) and emissions may raise the nitrate and ammonia concentrations in rainfall. Recent studies conducted in the Delaware Bay (Scudlark and Church, 1993) indicate that 26 percent of the summer total dissolved inorganic nitrogen flux is from atmospheric input. The 26 percent includes wet and dry deposition of nitrogen in the contributing watersheds to the Delaware Bay. Rainwater has also been considered as a potential source of elevated nitrate concentrations in springs. The City of Austin collected rainwater samples at the St. Elmo water quality pond, located in southeast Austin, during eight rain events in 1995 for a study of removal efficiencies of the water quality pond. Rainwater was analyzed for ammonia-nitrogen, total Kjeldahl nitrogen, nitrate+nitrite-nitrogen, total phosphorus, and dissolved phosphorus for each event (Table 2.6).

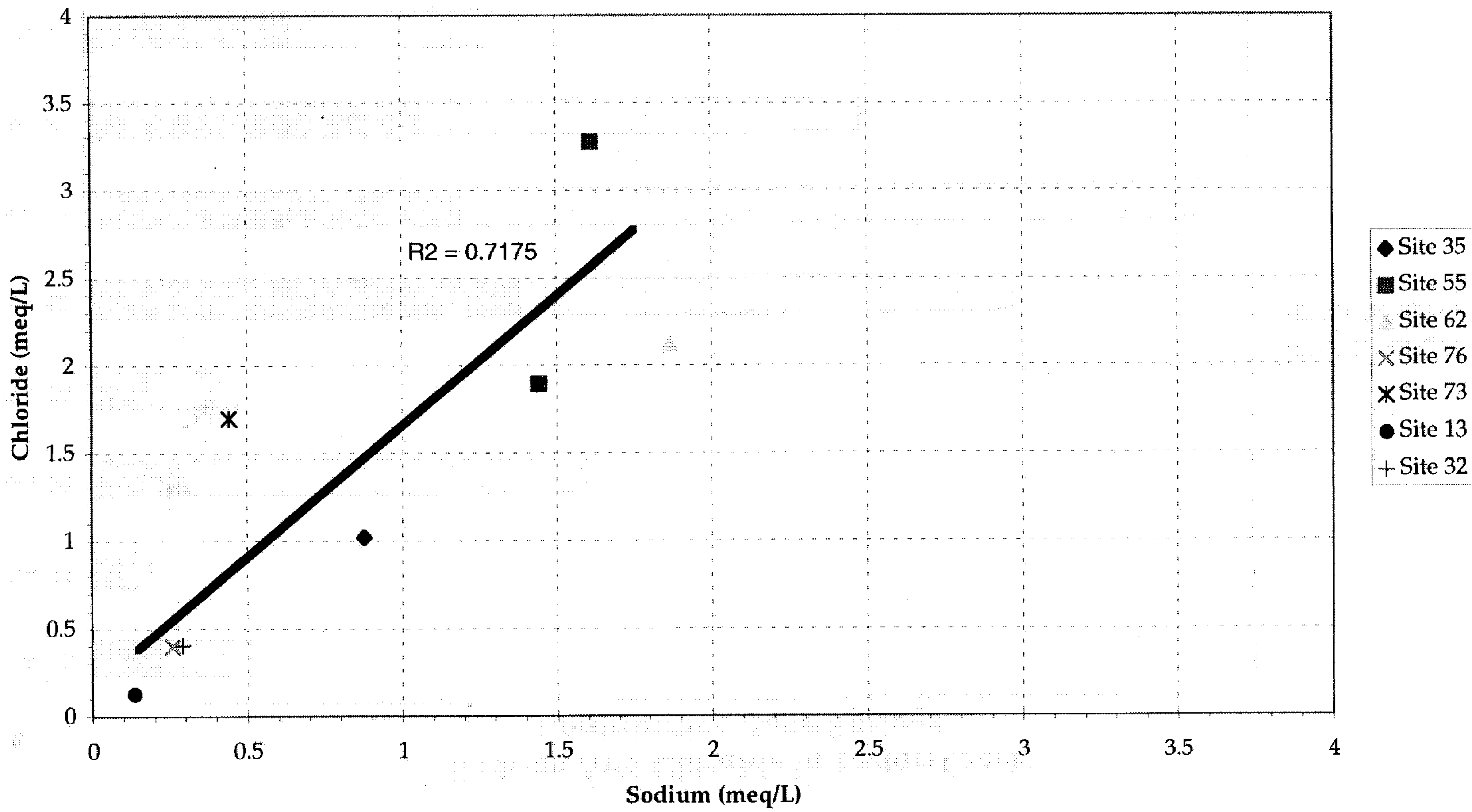
All but one of the TKN concentrations are below 1.99 mg/L. These rainfall concentrations represent the wet deposition and dry deposition of atmospheric inputs from industrial, agricultural, and vehicular sources in the Austin area. Based on these analyses, rainwater in urban areas contains insufficient nitrogen to totally account for concentrations detected in urban springs. Therefore, nitrogen values found in Sites 72/73 and 55 are indicative of an additional source of nitrogen and isotope data indicate this source to be effluent.

2.4.3.3 Ions

Ions such as Mg, K, Na, Cl^-, SO_4, and carbonates were used in the ground water studies as indicators of differences in water quality. These levels of ions may not indicate detrimental effects but merely the impact of urbanization or changes in geologic formation. Of the major ionic constituents in ground water, only magnesium is not in significantly different concentrations between urban and rural sites (Tables 2.3 and 2.4). Differences between the other constituents are not only significant but large.

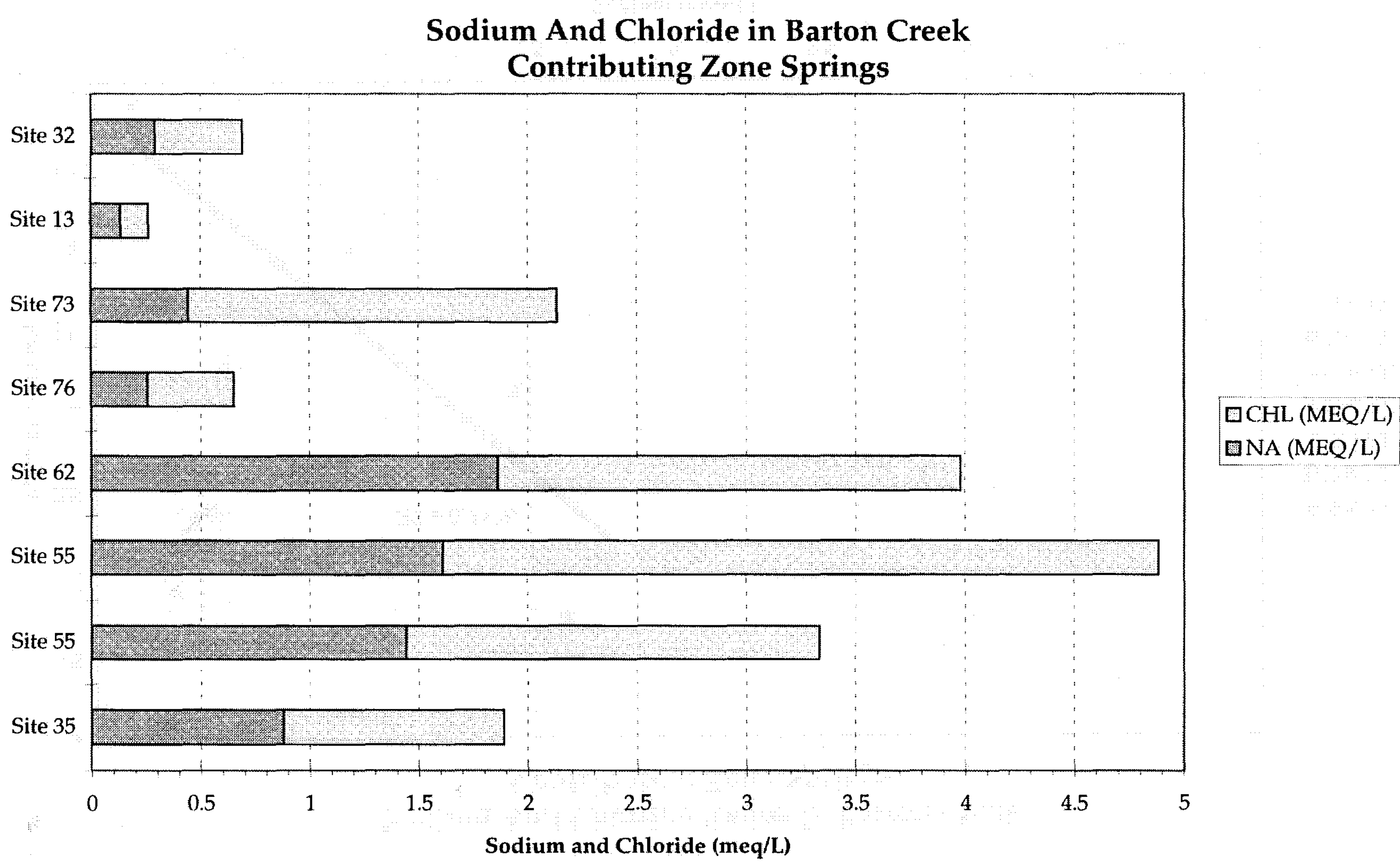
Figure 2.9

Sodium And Chloride Ratios In Barton Creek Contributing Zone Springs



Source: COA/DUD Database 1992-1996

Figure 2.10



Source: COA/DUD Database 1992-1996

Table 2.6 Rain Chemistry at St. Elmo Water Quality Pond, Austin, Texas

Date	NH3-N (mg/L)	TKN (mg/L)	NO3+NO2-N (mg/L)	Total P (mg/L)	Dissolved P (mg/L)
4/20/95	0.73	1.24	0.34	0.14	NA
4/22/95	1.33	1.66	0.88	0.10	0.03
5/8/95	0.43	1.36	0.26	0.07	NA
5/18/95	1.14	1.99	0.53	0.08	0.06
5/30/95	0.03	0.66	0.28	0.02	0.02
6/11/95	0.13	0.94	0.46	0.21	0.06
6/29/95	0.26	0.57	0.33	0.02	0.02
7/6/95	0.22	ND	0.44	0.03	0.02
Median concentration	0.53	1.07	0.44	0.08	0.04

Calcium is one of the major elements present in carbonate rocks and is usually the dominant cation in ground water in carbonate areas. Calcium concentrations in ground water in urban areas are 1.5 times higher in than rural areas (Table 2.4). Calcium concentrations range from 109 to 155 mg/L in urban sites and 54.2 to 116 mg/L in rural sites (Table 2.3).

Calcium sources are probably almost entirely from dissolution of carbonate rocks. In urbanized areas, high pH potable water may enhance dissolution of calcium-carbonate during irrigation, thereby increasing calcium concentrations in ground water. Treated wastewater effluent may have a similar effect. Although most soluble at low pH, calcite, the principle component of limestone, can be dissolved at the higher pH of potable water. This occurs when the water is undersaturated with respect to calcite. COA drinking water contains low concentrations of major ions, including alkalinity (Ca 17-20 mg/L, Mg 16-18 mg/L, Na 30-31 mg/L, Cl 56-59 mg/L, SO4 43-46 mg/L, alkalinity 15-31 mg/L (COA ,1996c)). Solubility diagrams (Freeze and Cherry, 1979) show this type of water under saturated with respect to calcite and, therefore, capable of dissolving limestone.

The mean of potassium concentrations is over five times higher in urban sites than in rural sites (Table 2.4). Concentrations range from 0.5 to 6.55 mg/L in urban sites compared to 0.52 to 0.85 mg/L in rural settings (Table 2.3). Factors which may increase potassium concentrations in urban settings are not known but may be related to increased dissolution of calcium-carbonate rocks from high pH irrigation waters or fertilizers.

The mean of sodium concentrations is over six times higher in urban sites than in rural sites (Table 2.4). Concentrations range from 5.96 to 120 mg/L in urban sites and 3.12 to 16.4 mg/L in rural sites (Table 2.3). Dissolution of halite (NaCl) is a naturally occurring source of sodium, although unlikely in the shallow subsurface of the Barton Creek Watershed. There are many manmade sources of sodium which can enter household sewage, including water softeners, bleach, and detergents. Irrigation with treated wastewater effluent would, therefore, be expected to increase sodium concentrations in ground water. The large number of samples in the data set from springs in areas that appear to be influenced by effluent irrigation probably skew the concentration averages upward. However, data from sites in the Bull Creek Watershed show a similar trend but with lower sodium concentrations in urban areas.

The mean of chloride concentrations in urban sites is nearly six times higher than in rural sites (Table 2.4). Concentrations range from 14 to 266 mg/L in urban sites compared to a range of 4.5 to 36.4 mg/L in rural sites (Table 2.4). As with sodium, dissolution of halite is a common natural source of chloride but large amounts of halite in the shallow subsurface of the Barton Creek Watershed is unlikely. Chloride is common in domestic wastewater from consumption of sodium chloride (table salt) (Csuros, 1994). Higher concentrations found in urban sites during this study are probably related to effluent irrigation.

The mean of sulfate concentrations in urban areas is approximately 3 times higher than concentrations in rural areas (Table 2.4). Two of the four data points in the undeveloped area had concentrations of 7.26, and 7.15 mg/L measured at Site 13. The remaining two data points are 50.6 mg/L, measured at Site 32, and 40 mg/L at Site 8. These concentrations are similar to those reported for spring locations in the urban area although less than the urban median concentration of 75.61 mg/L. Urban springs range from 27 to 220 mg/L sulfate. Low concentrations generally occurred during extended wet periods.

A natural sulfate source is thought to be gypsum within the Glen Rose Formation or possibly celestite, a strontium sulfate mineral (Senger and Kreitler, 1984). Celestite is found in Member 5 of the Glen Rose Formation. Barite, a barium-sulfate mineral, is another possible source and is a common mineral found in soils derived from limestone weathering. Introduced sulfate in urban areas may come from fertilizers, soil conditioners, wastewater, and possibly atmospheric sources.

Alkalinity is a measure of the carbonate species ions (HCO3, CO3) present in water and are typically reported as CaCO3. Alkalinities detected in the urban springs ranged from 253 to 446 mg/L and in the rural springs from 231 to 320 mg/L (Table 2.3). Higher alkalinity concentrations in ground water from residential areas served by sewer systems have been observed in Long Island, New York (Eckhardt and Stackelberg, 1995). It is likely that wastewater effluent irrigation, possibly domestic wastewater, or accelerated carbonate dissolution are the sources of elevated alkalinities observed for this study.

2.4.3.4 Total Organic Carbon

TOC values represent the organic carbon-bearing compounds present in ground water (Csuros, 1994). TOC values from urban springs range from 1.06 to 74.8 mg/L (Table 2.3). One sample was reported above a concentration of 5.0 mg/L. Three TOC values from rural springs range from below detection (<1.0) to 1.71 mg/L. The potential source of the organic carbon compounds in the urban springs has not been identified.

2.4.3.5 Bivariate Analysis

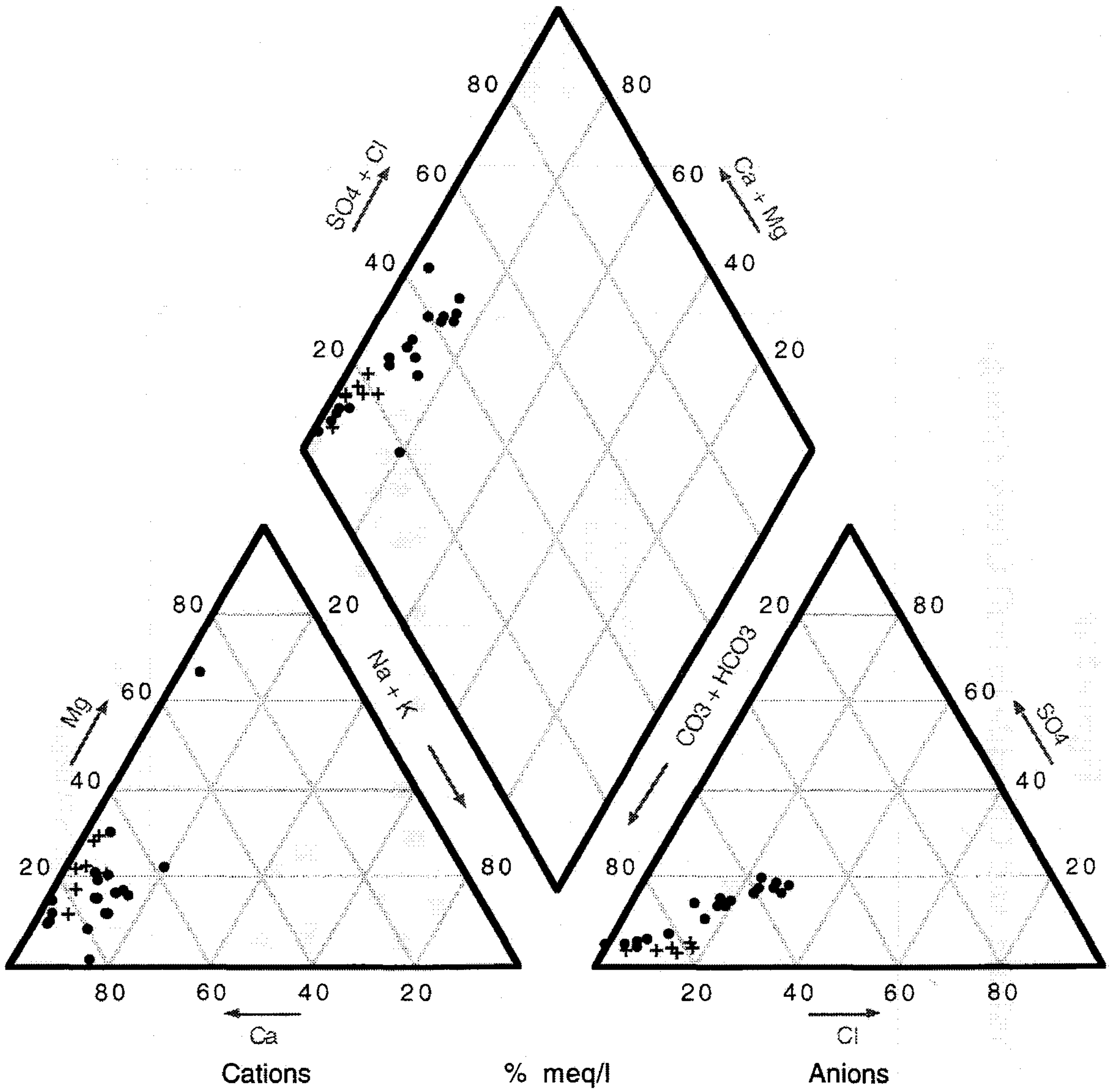
Bivariate analysis of springs in urban and rural settings was conducted to determine if there were any subtle relationships between chemical parameters. This data set is hampered by the low number of data points from rural springs and influenced by the number of wastewater irrigation spring sites. Interpretation of these data relies on more abundant water chemistry data from the Bull Creek Watershed.

COA studies of ground water from springs in the Bull Creek Watershed have identified differences in water chemistry between springs in urban areas and those in rural areas. These differences include total dissolved solids, nitrate-nitrogen, chloride, sulfate, potassium, sodium, calcium, and magnesium (COA, 1993b; Johns, 1994a). Piper plots of major ions illustrate this change in chemistry, particularly in anions, with rural ground water generally plotting below the 20 percent sulfate plus chloride line and urban ground water plotting above this line (Figure 2.11). Figure 2.12 illustrates the bivariate diagram used by Senger and Kreitler (1984) and Hauwert and Vickers (1994) to distinguish Glen Rose and deep Edwards waters from water in the Edwards recharge areas as applied to Bull Creek Watershed springs. In this case, the cause of the chemical differences is not deeper formation waters but is clearly related to urbanization. Figure 2.12 shows clear distinction between springs in urban settings and those in rural settings with urbanized springs being generally greater than 1.6 log SO4 and between -0.4 and 0.2 log SO4/Cl. High concentrations of sulfate in urban springs are the prime distinguishing factor for ion chemistry. Host rock geochemistry does appear to be a minor factor in these plots, as the lowest points along the SO4/Cl axis in the urban field tend to be Glen Rose springs.

Additional bivariate plots of Bull Creek spring water chemistry, for example nitrate-nitrogen and specific conductance values, provide more guidance in interpreting data from the BSEA and the CZ. Figure 2.13 shows a large spread in data points representing urban sites whereas rural sites are clustered. The few urban sites plotting with the rural sites are located in areas where development is in an early stage. Ground water at urban sites can be characterized by specific conductances greater than 800 us/cm and nitrate-nitrogen concentrations greater than 1.5 mg/L. Rural sites generally have values less than urban sites.

Figure 2.11

Bull Creek Rural and Urban Springs Ion Data

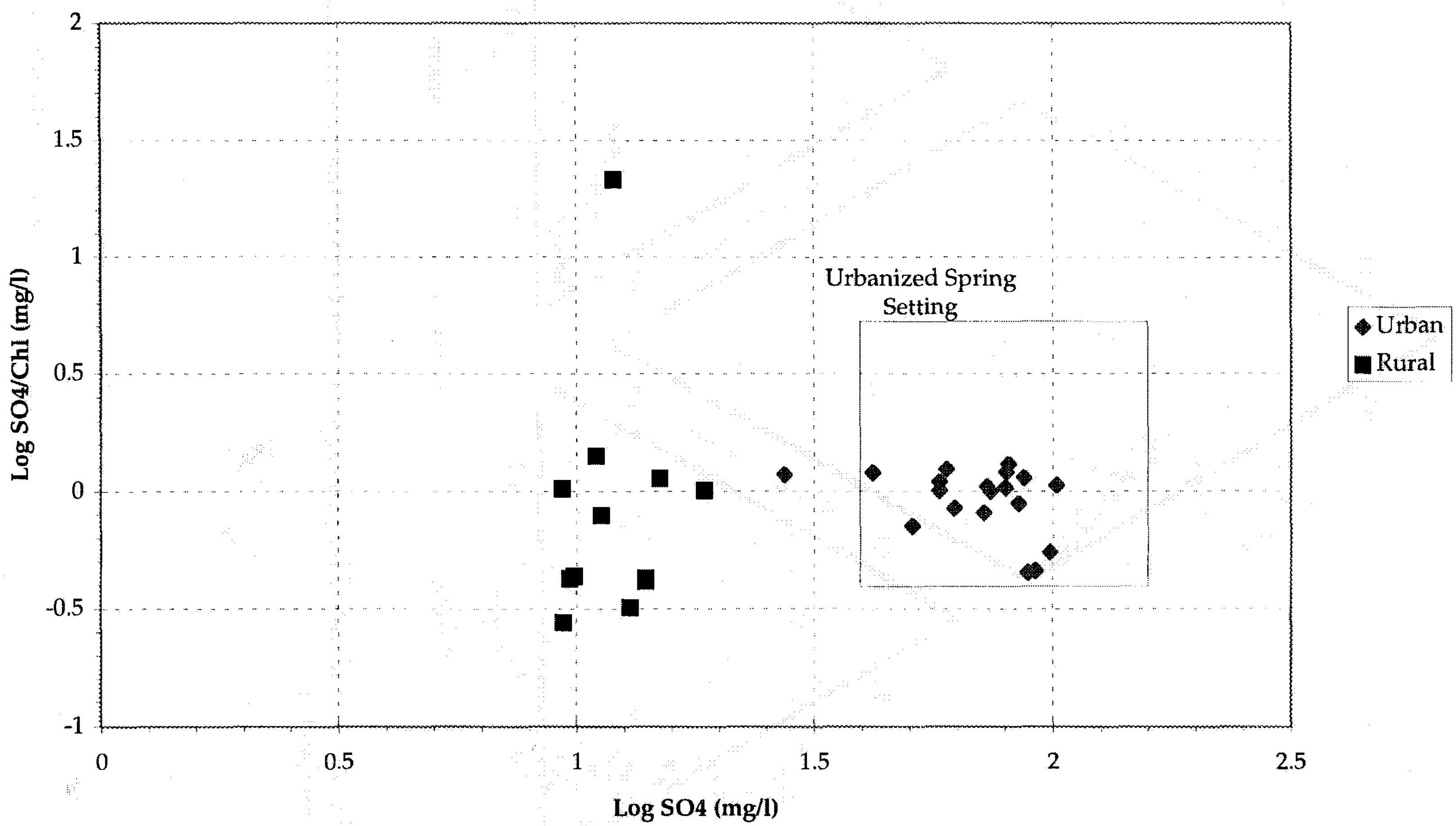


Rural sites are indicated by plus signs (+) and urban sites are indicated by filled circles (•).

Source: COA/DUD Database 1993-1995

Figure 2.12

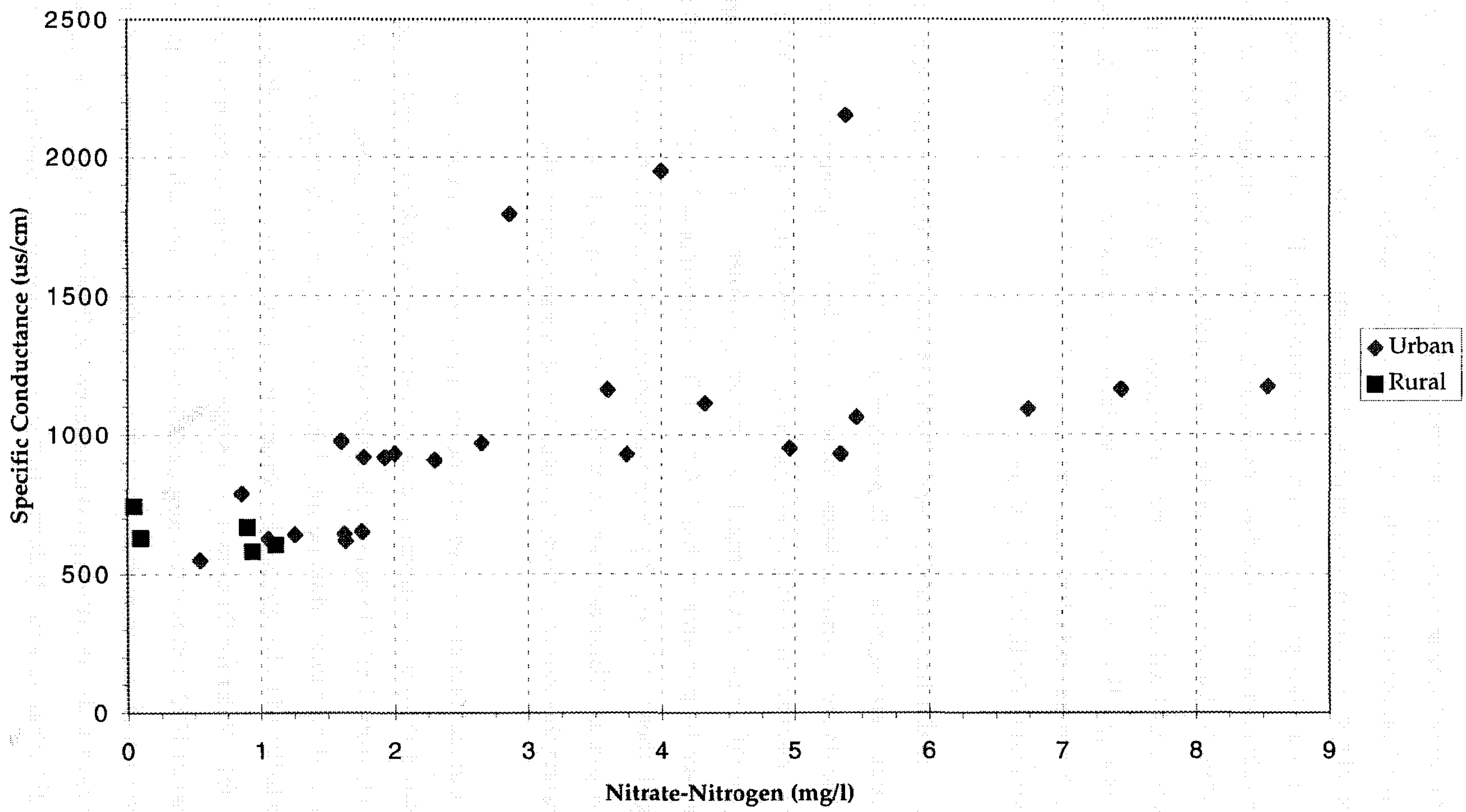
Sulfate And Chloride In Bull Creek Springs



Source:COA/DUD Database 1993-1995

Figure 2.13

Specific Conductance And Nitrate In Bull Creek Springs



Source: COA/DUD Database 1993-1996

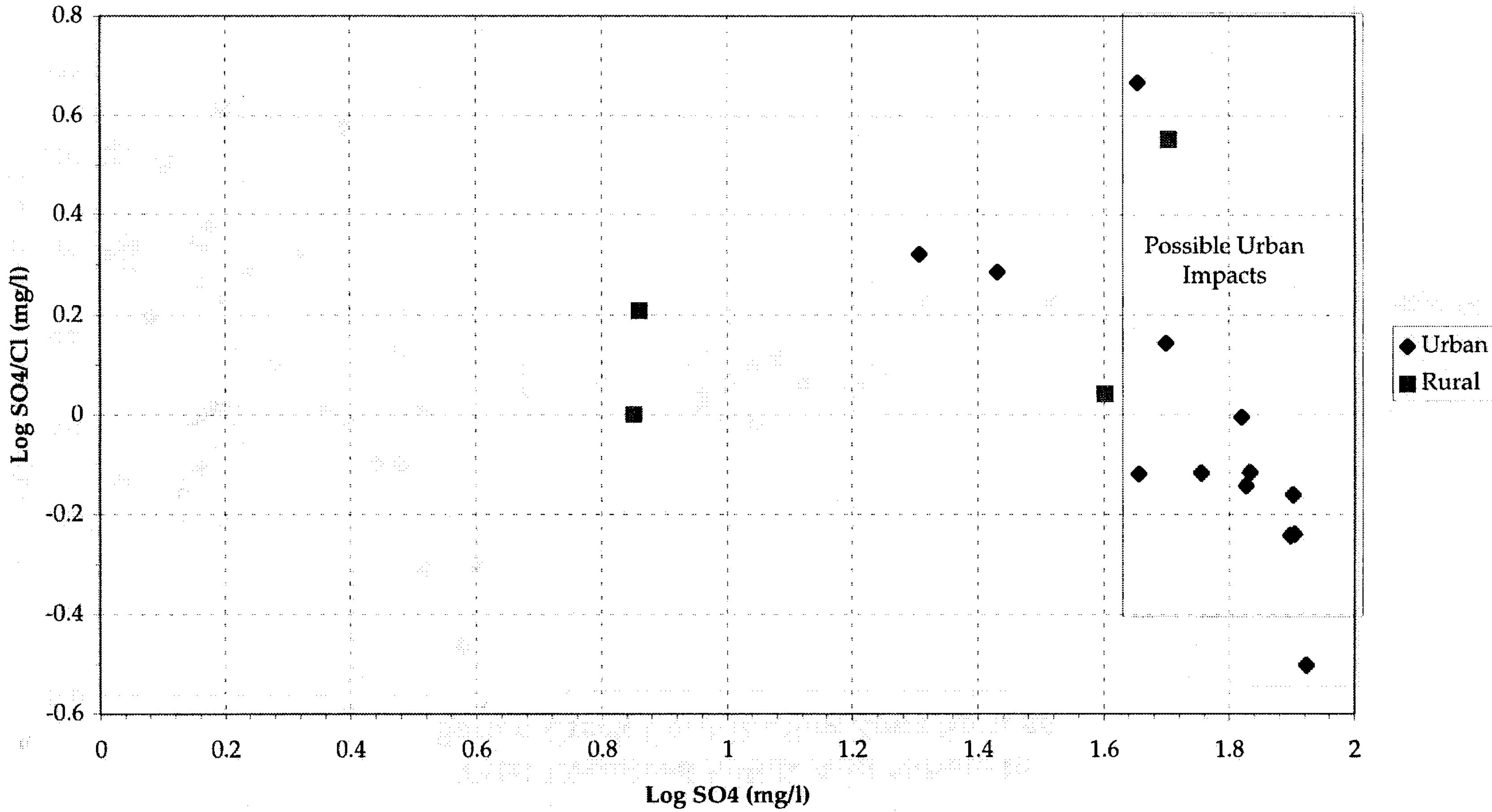
Figure 2.14 illustrates the relationship between chloride and sulfate for Barton Creek Contributing Zone springs in urban and rural settings. Significant differences occur in concentrations of these constituents between urban and rural sites. Two data points for a perennial spring in a rural ranch (Site 13) plot distinctly different from other data points. Two other "rural" data points plot within the urban field. These sites are potentially affected by urban activities: a major roadway over one (Site 32) and a single domestic septic field near the other (Site 8). Most of the urban data points plot within the field indicating possible urban impacts. This field is characterized by higher sulfate concentrations than found in springs in rural settings. The distinction between these cultural settings is consistent with data from the Edwards Group and Glen Rose Formation in both the Barton Springs segment of the Edwards Aquifer and in the Bull Creek Watershed.

Figure 2.15 illustrates the differences between two additional constituents, total dissolved solids and nitrate, with significant differences in concentrations from urban and rural sites. These constituents are commonly tested for in both surface and ground water. Samples from rural sites can be characterized by plotting below approximately 300 mg/L TDS (mean of 281 mg/L) and generally less than 0.5 mg/L nitrate-nitrogen (mean of 0.33 mg/L). Samples from urban sites generally plot greater than 300 mg/L TDS (mean of 447 mg/L) and 0.5 mg/L nitrate-nitrogen (mean of 1.6 mg/L). Some exceptions are present in the urban samples, plotting close to rural points. These samples were all collected during very wet conditions in 1992 and 1995, illustrating the diluting effects of abundant infiltrating rainwater.

Large fluctuations in ion chemistry occur at two spring locations: Site 55, and Site 72/73. The differences in water chemistry are most obvious in the anion chemistry. Enough data are available from Site 72 to develop a hypothesis of why these fluctuations are occurring. In Figure 2.14, two urban data points plotting outside the urban impacts field are from Site 72, a spring believed to be affected by effluent irrigation from a nearby golf course (see Appendix B, photo 3b). Water for these two points was collected during wet periods in early 1995 and summer of 1992. Other data from this site plot within the urban impact field. Closer examination of data from this spring shows that the water believed to be derived from treated wastewater is diluted during wet conditions. A Piper plot (Figure 2.16) of data collected from this spring (Site 72 and 73) during wet and dry conditions (based on Barton Creek flow and

Figure 2.14

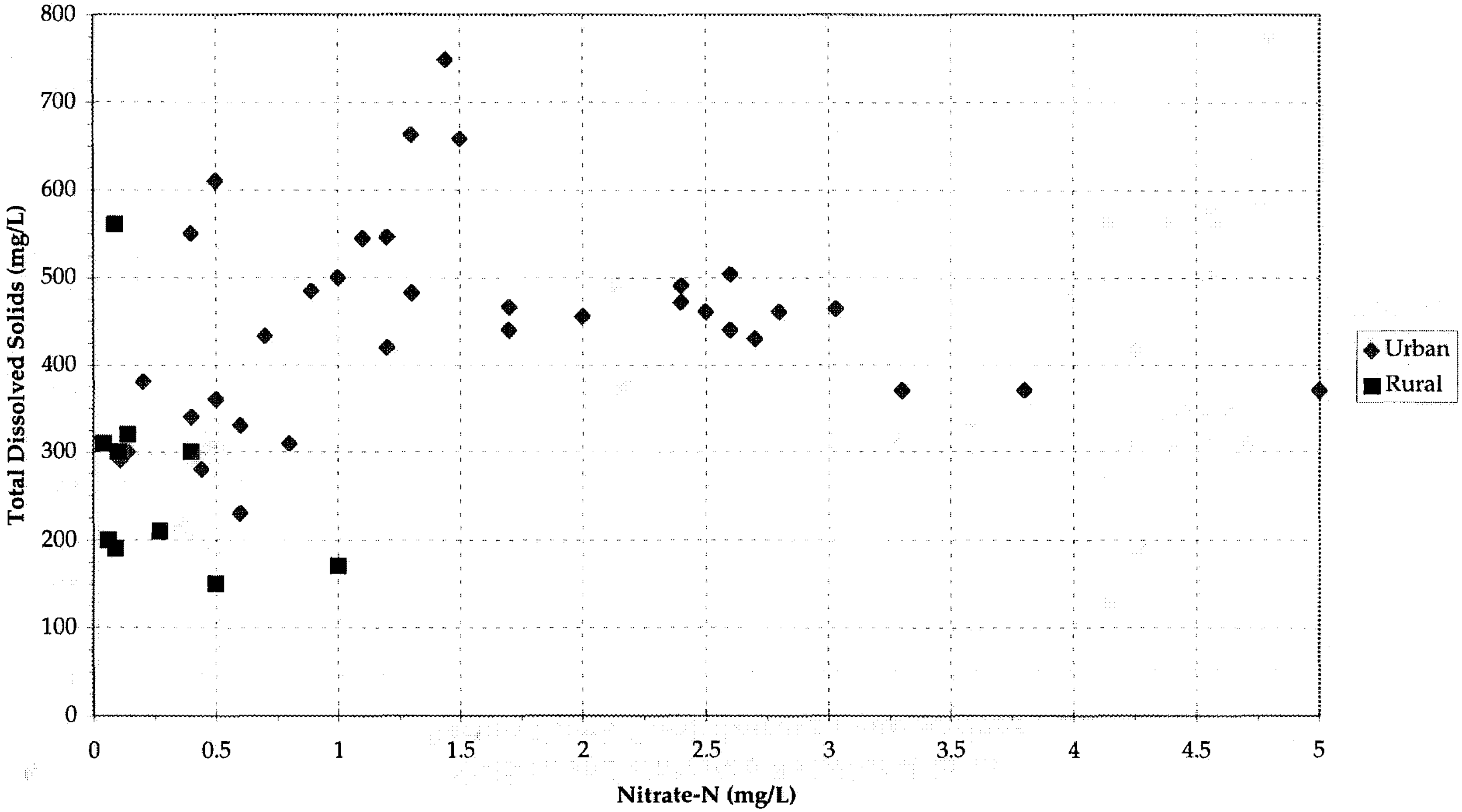
Sulfate and Chloride Relationship In Barton Creek Contributing Zone Springs



Source: COA/DUD Database 1992-1996

Figure 2.15

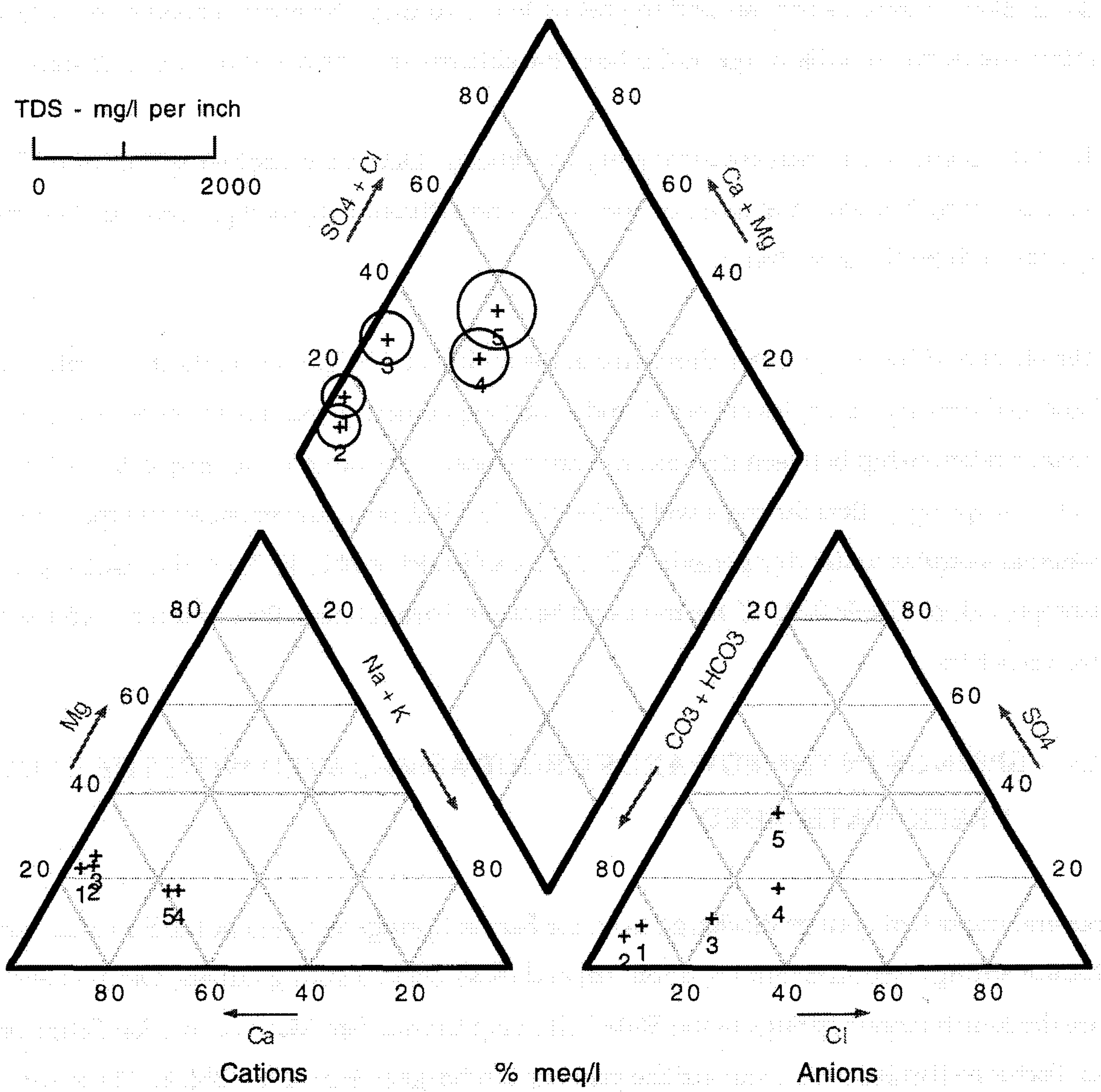
Total Dissolved Solids And Nitrate In Barton Creek Contributing Zone Springs



Source: COA/DUD Database 1992-1996

Figure 2.16

Site 72 High And Low Flow Ion Data



Site 72 Spring					
No.	TDS	Sample	No.	TDS	Sample
1	479	Site 72 7/7/92			
2	506	Site 72 2/22/95			
3	620	Site 72 8/29/95			
4	687	Site 72 5/14/96			
5	912	Site 72 9/25/96			

Barton Creek at Lost Creek flow measured at 28 cfs for 7/7/92, 16 cfs for 2/22/95, 0.61 cfs for 8/29/95, 0.12 cfs for 5/14/96, and 0.9 cfs for 9/25/96.

Source: COA/DUD Database, USGS Water Resources Data rainfall records) shows a clear dilution trend from dry conditions to wet conditions. During dry conditions most, if not all, water discharging from the spring is from irrigation water infiltrating the shallow alluvial sediments and migrating to the spring. During wet conditions, infiltrating rainwater dominates discharge and dilutes the effluent and the resulting chemical signature.

Total dissolved solids increase during dry conditions. Data from another spring, Site 55, in a similar setting but with a mixture of raw water and effluent irrigation practices in its watershed appear to show the same trend.

The effect of dilution on water chemistry in the spring at Site 72 is also reflected in nitrogen isotope chemistry. Samples collected under varying climatic conditions suggest a strong inverse relationship between dry and wet conditions. For example, samples collected for two different spring outlets during a wet period (2/22/95) show a low nitrogen isotope value whereas samples under dry periods of 2/22/94, 4/19/94, and 2/13/96 had considerably higher isotopic values (Table 2.5). R^2 for the trend between Barton Creek flow and nitrogen isotopic values is 0.968.

2.5 SPRINGS IN THE EDWARDS GROUP ASSOCIATED WITH THE BARTON CREEK WATERSHED

Several important springs discharge from the Barton Springs segment of the Edwards Aquifer. Barton Springs (see Appendix B, photo 1b) and its associated spring outlets, Old Mill and Eliza, are the fourth largest springs in the State, following Comal, San Marcos, and San Felipe Springs in discharge (Brune, 1981), and are the primary discharge point for the BSEA. These springs discharge into Barton Creek a few hundred feet from the confluence with Town Lake. Cold Springs discharges directly into Town Lake about three-fourths of a mile upstream of the MoPac bridge or 1.5 miles upstream of Barton Creek. Cold Springs discharges from a segment of the aquifer underlying the Rollingwood area which may not be directly connected to Barton Springs (Senger and Kreitler, 1984). However, recharge to the spring may include water from the upper end of the RZ in Barton Creek and hence its relevance to this study. No other large springs are known to discharge from this segment of the aquifer into Town Lake, based on historical records and a temperature survey conducted during the summer of 1996. However, numerous cavities are visible in Edwards outcrops along the south bank of Town Lake which probably represent ancient spring outlets. These conduits may still serve as overflow conduits, flowing only after heavy rain or during high water levels in the aquifer.

Backdoor Spring is a perennial spring on Barton Creek in the upper end of the RZ (see Appendix B, photo 2a). The recharge source for Backdoor is not clear but may include Barton Creek upstream of the spring, uplands south of the spring including the Travis Country area as far south as Oak Hill and tributaries such as Sycamore Creek near Travis Country. Campbell's Hole is a perennial pool on Barton Creek over the Recharge Zone about one mile upstream of Barton Springs (Espy Huston, 1979). There is no well defined spring outlet and no water data for this site; however, this site has water even under low flow conditions in the aquifer, based on field observations in summer 1996. The source of flow maintaining the pool is likely from perched water and not from the creek channel intersecting the regional water table. An informal temperature survey of the pool at Campbell's Hole in summer of 1996 showed the coolest water in the upstream portion of the pool near a large fault, possibly the conduit for discharge.

Table 2.7 summarizes results of recent COA sampling of BSEA springs.

2.5.1 Barton Springs

Barton Springs is the major discharge point for the BSEA. The springs issue from a fault, juxtaposing the Edwards on the west with the Georgetown on the east (Trippet and Garner, 1976), and associated fractures and Karst openings on the south side of Barton Springs Pool (see Appendix B, photo 1b). The main fault has been designated the Barton Springs Fault (Rodda and others, 1970). Under high flow conditions, water can be seen discharging from numerous small fractures along the south side of the pool. Under low flow conditions water is not generally seen discharging above the water level of the pool but can be felt slowly flowing from larger openings. Discharge is visible when the pool is lowered.

2.5.1.1 Discharge

Barton Springs has an average discharge of 50 cfs and a maximum discharge of 166 cfs in May 1941 and a minimum discharge of 9.6 cfs in March 1956 (USGS, 1995). Previous researchers have documented the close relationship between rainfall and rapid response in discharge from the springs (Slade and others, 1986). Spring discharge can increase 20-30 cfs within 24 hours following heavy rains and 65 cfs within days following very heavy rains. For example, Barton Springs discharge increased from 65 cfs to 130 cfs in four days (USGS, 1992) following 12 inches of rain over five days in December of 1991.

Previous water balance studies by Andrews and others (1984) and Slade and others (1986) indicate that water discharging from Barton Springs is primarily recharged in the channels of six creeks, Barton, Williamson, Slaughter, Bear, Little Bear, and Onion. Slade used flow measurements in the six creeks and compared that with discharge from Barton Springs to determine that 85 percent of the water discharging from the springs was recharged in these creeks. The remaining 15 percent recharges in upland zones, minor tributaries, or from leakage out of other aquifers. A recent water balance study by the CRWR (Barrett and Charbeneau, 1996) has revised the percentage of water each creek contributes, with Onion (46 percent) and Barton (31 percent) estimated to provide over 75 percent of the water discharging from the springs. A City of Austin consultant report (Santos, Loomis and Associates, 1995) determined that of the water recharging the aquifer in creek channels, 85 percent originated as base flow in the Contributing Zone and the remaining 15 percent originated as storm flow in the Contributing Zone or Recharge Zone. Barrett and Charbeneau (1996) report similar values: 9 percent of total creek recharge being derived from storm water runoff.

Flow loss measurements by the USGS and the BS/EACD indicate that recharge in Barton Creek is not uniform. Measurements by the USGS (Slade and others, 1986) illustrate this point quite well. Flow in Barton Creek at the beginning of the Recharge Zone was measured at 74.6 cfs.

Table 2.7
Summary of BSEA Springs Chemistry

SITE	pH	SpCond us/cm	Temp C	Turb NTU	DO mg/L	TOC mg/L	NH3-N mg/L	NO3-N mg/L	TKN mg/L	ORTHO P mg/L
Barton Springs										
Average	7.17	645	21.76	4	5.37	1.58	0.03	1.47	0.62	0.02
Median	7.07	648	21.35	0	5.47	1.4	0.02	1.47	0.22	0.02
Max	8.54	768	24	45	6.24	2.9	0.07	3.5	7.82	0.04
Min	6.26	431	20.2	0	3.61	0.79	0	0.7	0.1	0.01
Count	32	26	32	22	18	6	16	39	19	15
Non-Detections							22 ND		17 ND	25 ND
Eliza Spring										
Average	7.21	669	21.84	0.5	4.72	2.34	0	1.09	0.16	0.02
Median	7.08	656	21.6	0.5	4.72	1.96	0	1.11	0.16	0.02
Max	7.6	762	24	1	4.72	3.13	0	1.46	0.16	0.02
Min	6.96	603	20.4	0	4.72	1.94	0	0.6	0.16	0.02
Count	5	4	5	2	2	3	1	6	1	1
Non-Detections							5 ND		4 ND	5 ND
Old Mill Spring										
Average	7.28	828	22.09	1	5.82	5.58	0.01	1.16	0.26	0.01
Median	7.20	764	21.7	1	5.92	4.31	0.02	1.16	0.26	0.01
Max	7.7	1040	24	1	6.25	12.7	0.02	1.76	0.37	0.01
Min	7.07	674	20.4	0	5.3	1	0	0.693	0.14	0.004
Count	8	6	9	3	3	4	3	8	2	2
Non-Detections							5 ND		5 ND	6 ND
Cold Spring										
Average	7.27	565	21.25	1.75	7.03	1.56	0.056	1.18	0.16	0.08
Median	7.3	579	20.53	2	7.02	1.3	0.02	1.15	0.16	0.06
Max	7.95	644	26	3	8.3	3.01	0.27	2.36	0.16	0.21
Min	6.55	479	19.6	0	5.39	1	0	0.21	0.16	0.01
Count	22	17	20	4	11	5	17	26	2	14
Non-Detections							9 ND		9 ND	11 ND
Backdoor Spring										
Average	7.45	706	21.51	5.14	8.7	12.57	0.02	1.44	0.27	0.05
Median	7.46	692	22	1	8.7	4.15	0.02	1.50	0.30	0.02
Max	7.93	772	24	22	9.65	40.2	0.05	2.08	0.37	0.218
Min	7	686	19.7	0	7.75	1.78	0	0.9	0.15	0.02
Count	12	6	11	5	2	4	8	12	3	10
Non-Detections							4 ND		6 ND	2 ND

Source: COA/DUD Database 1992-1996

Table 2.7
Summary of BSEA Springs Chemistry

SITE	TP mg/L	FC colonies/100 ml	FS colonies/100 ml	TSS mg/L	SURFACTANTS	Diesel/Oil	TPH	COD	Ca mg/L
Barton Springs									
Average	0.04	453	297	2.88					78.1
Median	0.04	49	84	1					78.2
Max	0.11	2700	840	21	0	0	0	0	92.1
Min	0.02	1	0	0.06	0	0	0	0	63
Count	21	13	7	28	0	0	0	0	13
Non-Detections	14 ND	1 ND		6 ND	4 ND	3 ND	1 ND	5 ND	
Eliza Spring									
Average	0.035	8	33	2.4					86.1
Median	0.035	4	31	3					86.4
Max	0.05	23	55	3	0	0	0	0	97.7
Min	0.02	1	12	1.2	0	0	0	0	72.3
Count	4	5	3	3	0	0	0	0	5
Non-Detections	1 ND			2 ND	1 ND			2 ND	
Old Mill Spring									
Average	0.06	21	17	1.6					83.1
Median	0.03	5	15	2					84.9
Max	0.18	93	36	2	0	0	0	0	90.4
Min	0.03	1	1	0.8	0	0	0	0	71.5
Count	6	7	4	3	0	0	0	0	8
Non-Detections	1 ND	1 ND		4 ND	1 ND		1 ND	2 ND	
Cold Spring									
Average	0.07	66	35	1.4			0.085		76.5
Median	0.03	9	32	0.8			0.085		75.4
Max	0.311	532	78	4	0	0	0.085	0	91
Min	0.02	0	1	0	0	0	0.085	0	71.3
Count	9	20	7	4	0	0	1	0	10
Non-Detections	2 ND	3 ND		5 ND	2 ND		1 ND	3 ND	
Backdoor Spring									
Average	0.05	3	168	1					96.6
Median	0.04	2	140	1					93.8
Max	0.11	5	392	1	0	0	0	0	120
Min	0.02	0	0	1	0	0	0	0	86.3
Count	6	6	4	2	0	0	0	0	9
Non-Detections	2 ND	2 ND		6 ND	1 ND		1 ND	3 ND	

Source: COA/DUD Database 1992-1996

Table 2.7
Summary of BSEA Springs Chemistry

Mg mg/L	SITE	Na mg/L	K mg/L	Chl mg/L	SO4 mg/L	Fl mg/L	ALKALINITY mg/L (HCO3)	Sb mg/L	As mg/L	Ba mg/L
	Barton Springs									
21.9	Average	19.6	1.56	34.2	36.6	0.26	258		0.046	0.050
21.2	Median	18.3	1.49	26.8	34.4	0.23	256		0.046	0.051
28	Max	38.2	8	67.5	52	0.65	266	0	0.046	0.056
16.9	Min	11.2	1.02	18	25	0.19	250	0	0.046	0.044
13	Count	13	13	12	12	8	10	0	1	5
	Non-Detections					1 ND		5 ND	11 ND	
	Eliza Spring									
20.8	Average	18.3	1.26	30.8	34	0.26	263			
19	Median	14.7	1.2	27.3	35.6	0.26	262			
24.4	Max	29	1.48	53	46.9	0.32	273	0	0	0
18.3	Min	12.1	1.05	10.3	13.6	0.2	255	0	0	0
5	Count	5	5	5	5	2	5	0	0	0
	Non-Detections					2 ND			5 ND	
	Old Mill Spring									
22.9	Average	37.5	1.86	66.6	54.6	0.272	256			0.051
22.5	Median	31.6	1.79	57.2	49.2	0.24	254			0.046
26.2	Max	62.4	2.49	117	84.3	0.36	278	0	0	0.06
19.1	Min	21.5	1.4	23.3	32.1	0.2	245	0	0	0.046
8	Count	8	8	7	7	5	6	0	0	3
	Non-Detections					1 ND		2 ND	8 ND	
	Cold Spring									
20.6	Average	10.0	1.01	18.8	26.6	0.174	243		0.0768	0.082
20.65	Median	9.61	1.07	18.6	26.7	0.19	250		0.0768	0.074
23	Max	13.66	1.39	26	32.1	0.203	262	0	0.0768	0.13
19	Min	7.82	0.58	14	20	0.12	210	0	0.0768	0.051
10	Count	10	8	11	11	9	11	0	1	4
	Non-Detections		1 ND			1 ND		2 ND	9 ND	
	Backdoor Spring									
24.4	Average	12.4	1.14	25.1	12.0	0.16	303			0.0555
24.4	Median	11.2	1.00	22.6	10.4	0.155	313			0.0555
26.49	Max	19	1.78	40.6	20.4	0.2	326	0	0	0.057
22.6	Min	9.61	0.78	19.2	7	0.13	220	0	0	0.054
9	Count	9	4	9	9	4	9	0	0	2
	Non-Detections		4 ND			4 ND		2 ND	8 ND	

Source: COA/DUD Database 1992-1996

Table 2.7
Summary of BSEA Springs Chemistry

Be mg/L	SITE	Cd mg/L	Cr mg/L	Cu mg/L	Fe mg/L	Pb mg/L	Mn mg/L	Hg mg/L	Mo mg/L	Ni mg/L
	Barton Springs									
	Average	0.002		0.008	0.0795305		0.008			0.005
	Median	0.002		0.006	0.061		0.01			0.005
0	Max	0.002	0	0.017	0.179	0	0.012	0	0	0.008
0	Min	0.002	0	0.003	0.006183	0	0.003	0	0	0.002
0	Count	1	0	4	6	0	3	0	0	2
5 ND	Non-Detections	6 ND	7 ND	8 ND	6 ND	12 ND	2 ND	4 ND	5 ND	7 ND
	Eliza Spring									
	Average			0.009	0.069615	0.0015				0.004
	Median			0.009	0.085	0.0015				0.004
0	Max	0	0	0.009	0.12	0.002	0	0	0	0.004
0	Min	0	0	0.009	0.003845	0.001	0	0	0	0.004
0	Count	0	0	1	3	2	0	0	0	1
	Non-Detections			4 ND	2 ND	3 ND				2 ND
	Old Mill Spring									
	Average			0.006	0.042		0.004			0.009
	Median			0.006	0.045		0.004			0.009
0	Max	0	0	0.006	0.059	0	0.005	0	0	0.009
0	Min	0	0	0.006	0.02	0	0.002	0	0	0.009
0	Count	0	0	1	4	0	2	0	0	1
2 ND	Non-Detections	3 ND	3 ND	7 ND	4 ND	8 ND	1 ND	2 ND	3 ND	5 ND
	Cold Spring									
	Average			0.012	0.855	0.005				0.005
	Median			0.012	0.0465	0.005				0.002
0	Max	0	0	0.018	3.31	0.005	0	0	0	0.01
0	Min	0	0	0.006	0.017	0.005	0	0	0	0.002
0	Count	0	0	2	4	1	0	0	0	3
2 ND	Non-Detections	4 ND	4 ND	8 ND	6 ND	9 ND	4 ND	4 ND	2 ND	4 ND
	Backdoor Spring									
	Average				0.119	0.001				0.019
	Median				0.12	0.001				0.019
0	Max	0	0	0	0.22	0.001	0	0	0	0.019
0	Min	0	0	0	0.016	0.001	0	0	0	0.019
0	Count	0	0	0	3	1	0	0	0	1
1 ND	Non-Detections	2 ND	2 ND	8 ND	5 ND	7 ND	2 ND	2 ND	2 ND	6 ND

Source: COA/DUD Database 1992-1996

Table 2.7
Summary of BSEA Springs Chemistry

Se mg/L	SITE	Ag mg/L	Sr mg/L	Thl mg/L	Zn mg/L
	Barton Springs				
	Average		1.158	0.006	
	Median		1.06	0.006	
0	Max	0	2.16	0.006	0
0	Min	0	0.679	0.006	0
0	Count	0	5	1	0
5 ND	Non-Detections	5 ND		4 ND	5 ND
	Eliza Spring				
	Average				
	Median				
0	Max	0	0	0	0
0	Min	0	0	0	0
0	Count	0	0	0	0
	Non-Detections				
	Old Mill Spring				
	Average		0.821		
	Median		0.821		
0	Max	0	0.843	0	0
0	Min	0	0.798	0	0
0	Count	0	2	0	0
3 ND	Non-Detections	3 ND		2 ND	3 ND
	Cold Spring				
	Average		0.254		0.04
	Median		0.245		0.04
0	Max	0	0.3	0	0.04
0	Min	0	0.216	0	0.04
0	Count	0	3	0	1
4 ND	Non-Detections	4 ND		2 ND	3 ND
	Backdoor Spring				
	Average	0.009			
	Median	0.009			
0	Max	0.009	0	0	0
0	Min	0.009	0	0	0
0	Count	1	0	0	0
2 ND	Non-Detections	1 ND	1 ND	1 ND	2 ND

Source: COA/DUD Database 1992-1996

Average flow loss, or recharge to the aquifer, between the beginning of the Recharge Zone and Loop 360 was approximately 1.7 cfs/1000 ft of channel. Between Loop 360 and the north end of the Gus Fruh Park meander bend, flow loss was much greater, 2.7 cfs/1000 ft. This is also the area that the Barton Springs Fault crosses Barton Creek (Garner and Young, 1976; Hanson and others, 1996).

The difference in flow loss in different creek segments is probably most dependent on the number and size of point recharge features in the creek channel which may be related to particular geologic strata. Barton Creek makes a series of sharp turns in its course in the reach downstream of the MoPac bridge to the lower end of Gus Fruh Park. These sharp bends are likely due to structural influence and/or related solutional processes (Woodruff, 1986). Flow loss is also probably dependent on water levels in the aquifer and creek flow, as higher flow generates greater hydrologic head over recharge features.

During high water tables (also high discharge from Barton Springs) the lower part of Barton Creek upstream of Barton Springs Pool changes from a losing creek where water is recharging the aquifer to a gaining creek where water is discharging into the channel from the aquifer. During the USGS study (Barton Springs discharge of 77 cfs (USGS, 1982)), flow increased in Barton Creek by over four cfs from north of Gus Fruh Park to Barton Springs Pool. During very high aquifer water levels following heavy rains during December 1991 (Barton Springs discharge of over 100 cfs), large springs (estimated at one to three cfs) in Gus Fruh Park were discharging from cliff walls 10-15 feet above the channel floor. COA staff estimated that the creek was gaining flow from at least Loop 360 downstream to the pool, although no physical measurements were taken.

2.5.1.2 Chemistry

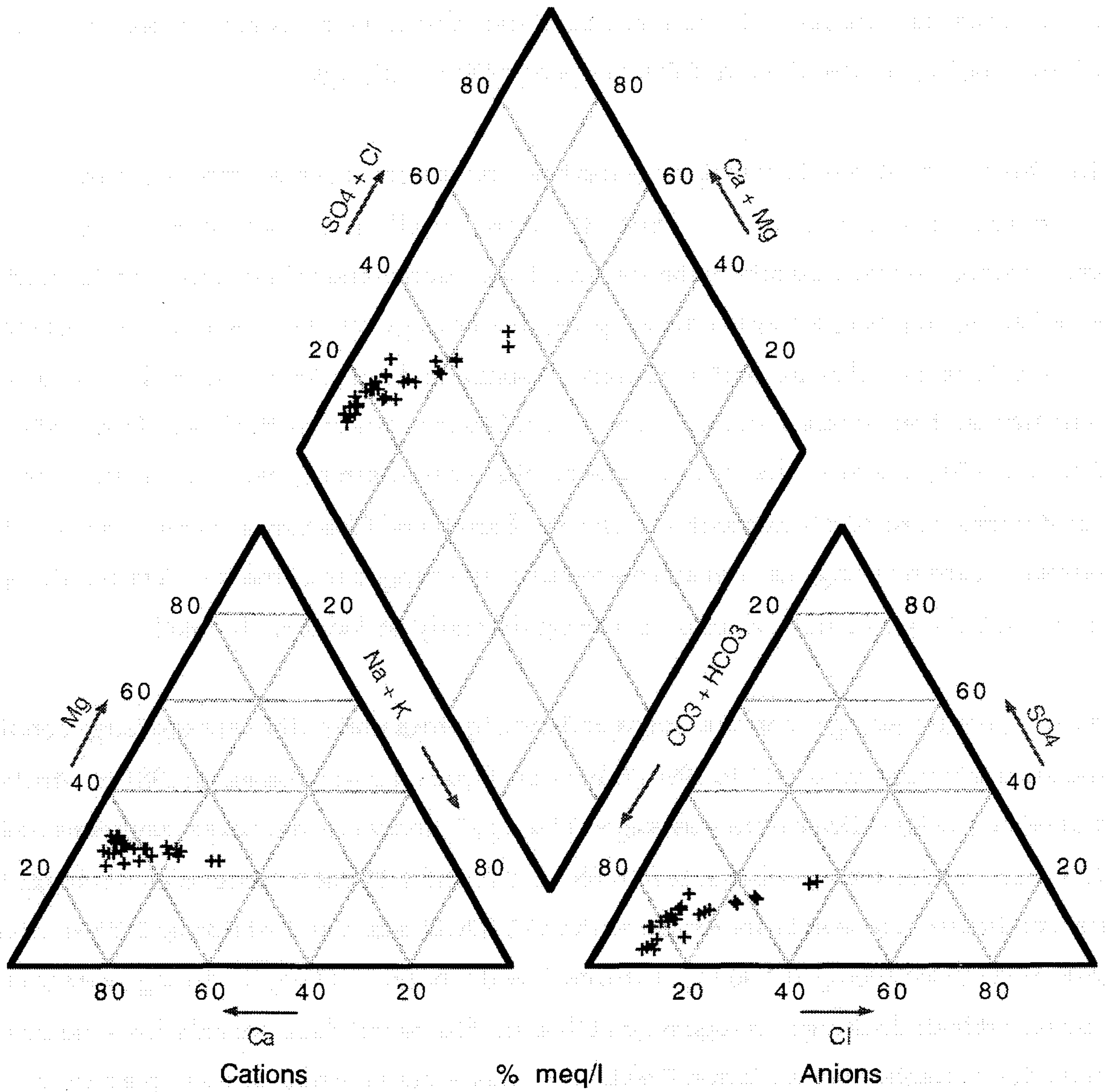
Geochemically, Barton Springs water is a calcium-bicarbonate type water. Data from this study and others show that Barton Springs plots consistently in a relatively narrow field on Piper diagrams (Figure 2.17), trending slightly toward enrichment in sodium, chloride, and sulfate during low flow conditions (Senger and Kreitler, 1984; Slade and others, 1986). During high flow conditions, particularly when the aquifer is receiving large volumes of recharge, Barton Springs plots close to surface water. This is indicative of the rapid nature of ground water migration in the Edwards when water has less contact time with host rocks and may reflect the large volume of recharge to the aquifer from Barton Creek relatively close to the springs. Table 2.7 summarizes results of recent COA sampling of BSEA springs.

The chemical quality of Barton Springs has been the subject of considerable scrutiny as environmental and land speculator interests debate the effects or potential effects of urbanization on water quality of the springs. These examinations have primarily focused on whether the quality of water in Barton Springs has changed through the years. Unfortunately, historical chemical data for Barton Springs are sparse and not adequate to evaluate long term time trends. Time trends based on more recent chemical data from the USGS, late 1970's through 1990's, are inconclusive as to whether there have been increases in concentrations of constituents, particularly nutrients and metals. Barrett and Charbeneau (1996) conclude that nitrate in Barton Springs has remained essentially unchanged over the last 15 years, although the overall change in impervious cover during the study period is fairly small.

Average nitrate-nitrogen concentrations at Barton Springs under different discharge conditions remain unchanged from 1981 to 1996 (Table 2.8). Detailed data collected in 1981-82 (Andrews and others, 1984) indicate nitrate averaged 1.54 mg/L under low discharge conditions (<40 cfs), 1.41 mg/L under average discharge (40<BS<60 cfs), and 1.21 mg/L under high discharge (>60 cfs) conditions. These data are similar with COA/DUD data collected during 1995-96 which indicated nitrate averaged 1.46 mg/L during low discharge, 1.48 mg/L during average creeks. The recent high discharge average is great than in 1981-82 but there are only five data points and other variables such as Barton Creek flow, antecedent moisture, and sample collection times relative to rainfall must be evaluated before any conclusions can be drawn. Several unusual chemical constituents have been detected in Barton Springs. There have been several documented occurrences of tetrachloroethylene in Barton Springs beginning in 1989 and ending in 1993 (USGS, 1989, 1990, 1991, 1992, 1993). Concentrations ranged from 0.2 to 1.7 ug/L. Additional samples collected in 1995 and 1996 have not detected this compound. As this chemical is anthropogenic in origin, there can be little doubt that human activities, dumping or illegal discharges to storm sewers, or leaking storage tanks, caused the contamination.

Figure 2.17

Barton, Old Mill, Eliza, Cold, and Backdoor Springs Ion Data



Data points represent results from samples collected from Barton, Old Mill, Eliza, Cold, and Backdoor Springs over the same time period.

Source: COA/DUD Database 1994-1996

Table 2.8 Barton Springs Discharge/Nitrate Values

DISCHARGE STAGE cfs	NO3-N mg/L	SOURCE AND SAMPLE SIZE
		USGS 1981-82
BS<40	1.54	n=5
40<BS<60	1.41	n=28
BS>60	1.21	n=29
		ATCHHSD 1986-95
BS<40	1.45	n=27
40<BS<60	1.35	n=21
BS>60	1.26	n=49
		COA/DUD 1995-96
BS<40	1.46	n=18
40<BS<60	1.48	n=6
BS>60	1.40	n=6

Several heavy metals are commonly detected in Barton Springs water, including arsenic, barium, copper, iron, lead, selenium, and zinc (Andrews and others, 1984; USGS, 1989 - 1995). It is unclear if these are present due to human activities, although it is unlikely that natural concentrations of metals such as lead, arsenic, and zinc are sufficient to sustain detectable concentrations in transient ground water. Heavy metals were more commonly detected in samples collected following storms than during base flow conditions.

Several factors complicate time trend analysis, including natural variation in chemical concentration, rapid migration of storm waters in the aquifer, timing of sample collection in relation to storms, and the relationship of spring discharge volume to constituent concentrations (i.e. they decrease as flow increases). Senger and Kreitler (1984) documented the inverse relationship of discharge to sodium, chloride, and sulfate concentrations. Their evidence indicated that during periods of low discharge, water from the "bad-water" line crept into the main body of the aquifer, mixed with fresher aquifer water, increasing constituent concentrations, and discharged from Barton Springs. Andrews and others (1984) and Slade and others (1986) documented the relationship between bacteria and rainfall and illustrated the relationship between high discharge volumes and low specific conductance. Andrews also noted the inverse relationship between recharge volume and nitrate-nitrogen. Slade (1986) and Slade and others (1986) documented the correlation between heavy rainfall and high turbidity in Barton Springs.

COA staff analysis of data collected since these early 1980's reports generally confirms the trends previously discussed. Analysis of data collected by the USGS from 1978 to 1993 indicates that turbidity and bacteria are higher in spring samples following storms (as defined in data sets as samples with bacteria concentrations greater than 100 colonies/100 ml) and specific conductance and magnesium were lower following storms. A number of chemical constituents are inversely related to spring discharge (i.e. they decrease as flow increases). These include total dissolved solids, specific conductance, nitrate-nitrogen, total nitrogen, magnesium, sodium, chloride, sulfate, and fluoride. Dissolved oxygen is directly related to discharge with high concentrations during periods of high spring discharge. T-tests of chemical constituents based on high flow verses low flow, with low flow being defined as spring discharge of less than 50 cfs, indicate a number of constituent trends related to flow conditions. Alkalinity, total dissolved solids, nitrate-nitrogen, hardness, magnesium, sodium, chloride, sulfate, and fluoride were all in lower concentrations during high discharge conditions. Dissolved oxygen and total suspended solids and fecal coliform bacteria were all higher during high discharge conditions.

A detailed analysis of nitrate-nitrogen indicates a well defined correlation between median nitrate-nitrogen concentrations and median rainfall totals (National Weather Service, 1996). Figure 2.18 illustrates a bimodal distribution of low nitrate-nitrogen concentrations in Barton Springs (based on ATCHHSD data from 1986-1995) in May and June and again in October and November which corresponds to bimodal high rainfall medians during the same months. Separate time trends for monthly nitrate-nitrogen data from the ATCHHSD from 1985-1995 show that nitrate-nitrogen concentrations have been decreasing over this time interval, inversely correlating with generally increasing rainfall median totals. Future analysis of nutrient trends and all other chemical trends in Barton Springs must factor in rainfall and recharge to determine if constituent concentrations are changing over time in the springs.

2.5.1.3 Data From *In-situ* Data Loggers

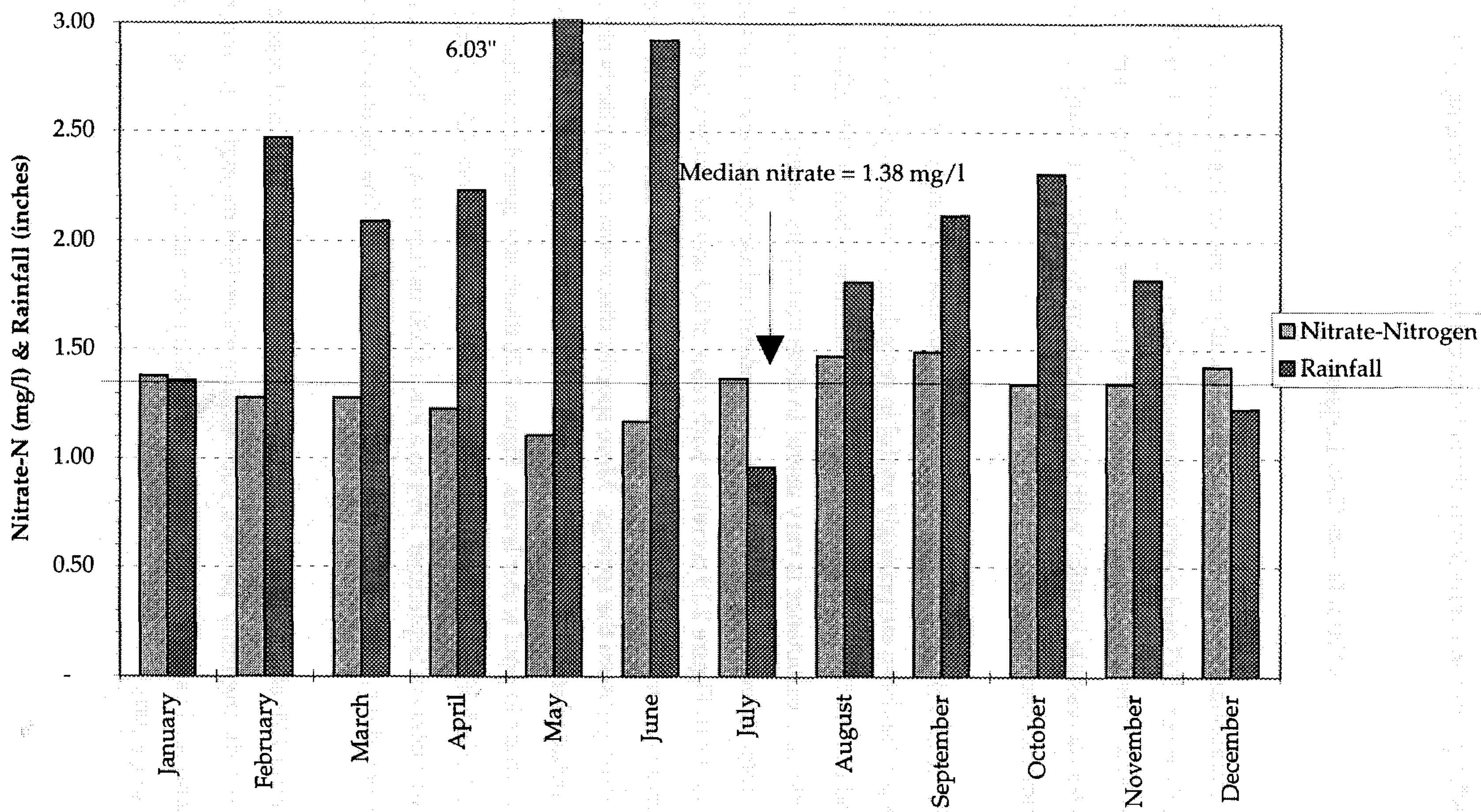
A DataSonde has been deployed periodically in the springs from March 1993 through September 1993 and nearly continuously since April 1994. The first deployment location proved to be too accessible and the unit was tampered with regularly, affecting data collection. A less accessible location with better exposure to spring discharge has been used since July 1994 with excellent data collection.

Figure 2.19 illustrates a record of depth and specific conductance during a typical month. Depth has been surprisingly useful in recording changes in pool water levels for maintenance and during flooding as well as helping determine when the DataSonde has been tampered with. Specific conductance is very useful in determining the timing of storm water impacts to the springs as well as providing data for understanding aquifer dynamics and structure. The troughs in Figure 2.19 correlate with rains of 0.9 and 3.6 inches (as measured by COA Flood Early Warning System, FEWS) when less mineralized rain water recharges the aquifer and discharges from the springs. More specific discussion of the effects of rainfall on Barton Springs is included in the Section 2.5.1.4 of this report. The spikes in specific conductance correlate with the drops in pool water levels. Figure 2.20 illustrates specific conductance of the springs over the period of record, ranging from a high of approximately 725 us/cm (microsiemens per centimeter) in September 1994 to a low of 530 us/cm in April 1995. Short term troughs, lasting several days, have even lower specific conductance following large rain events.

Figure 2.20 also shows the changes that occur resulting from recharge of large volumes of water during rainy periods, such as November 1994 through September 1995, as well as steady increases in specific conductance following extended dry weather as seen in April 1994 through August 1994.

Figure 2.18

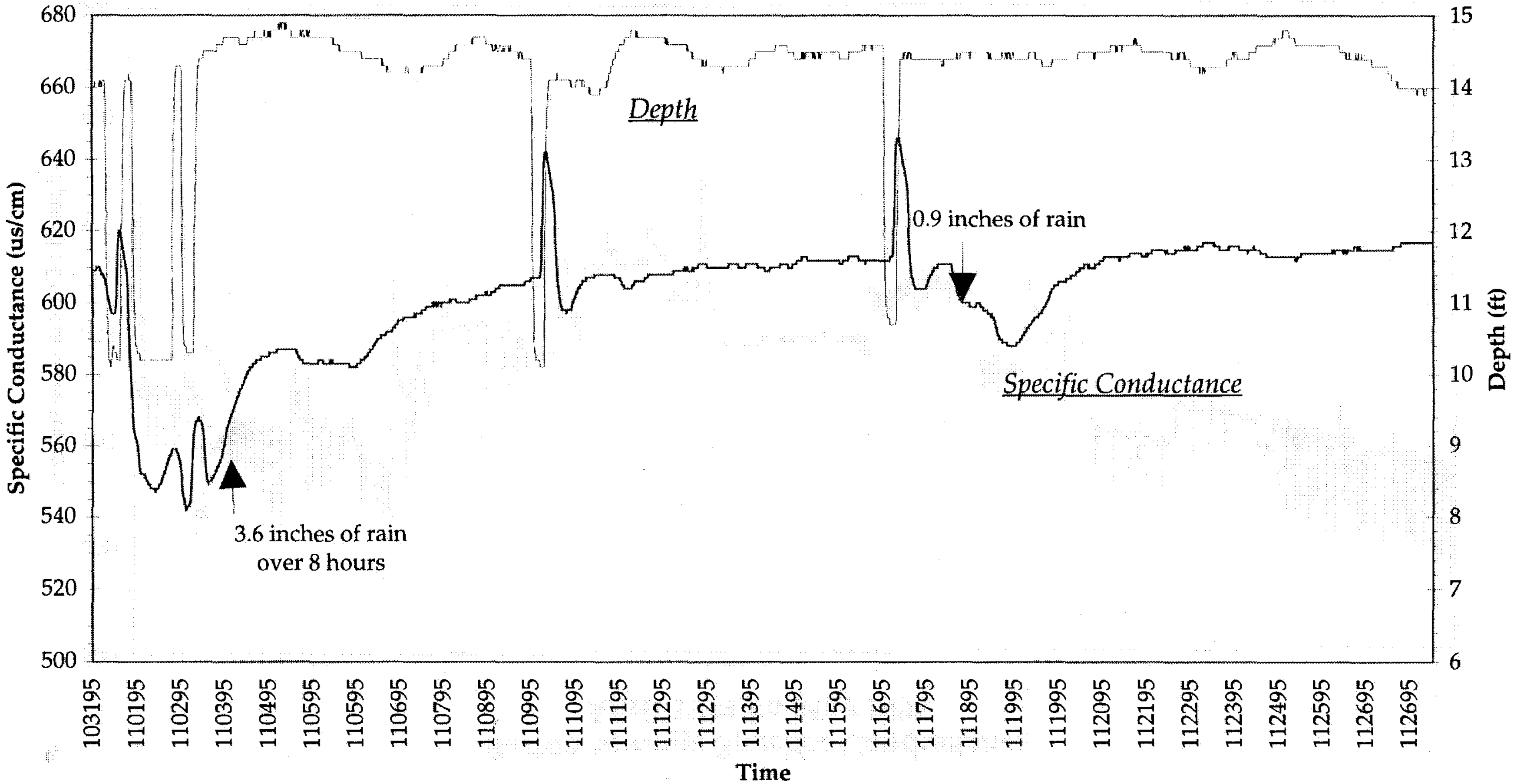
Barton Springs Nitrate and Rainfall Medians, 1986-1995



Source:COA/ATCHD Database and National Weather Service

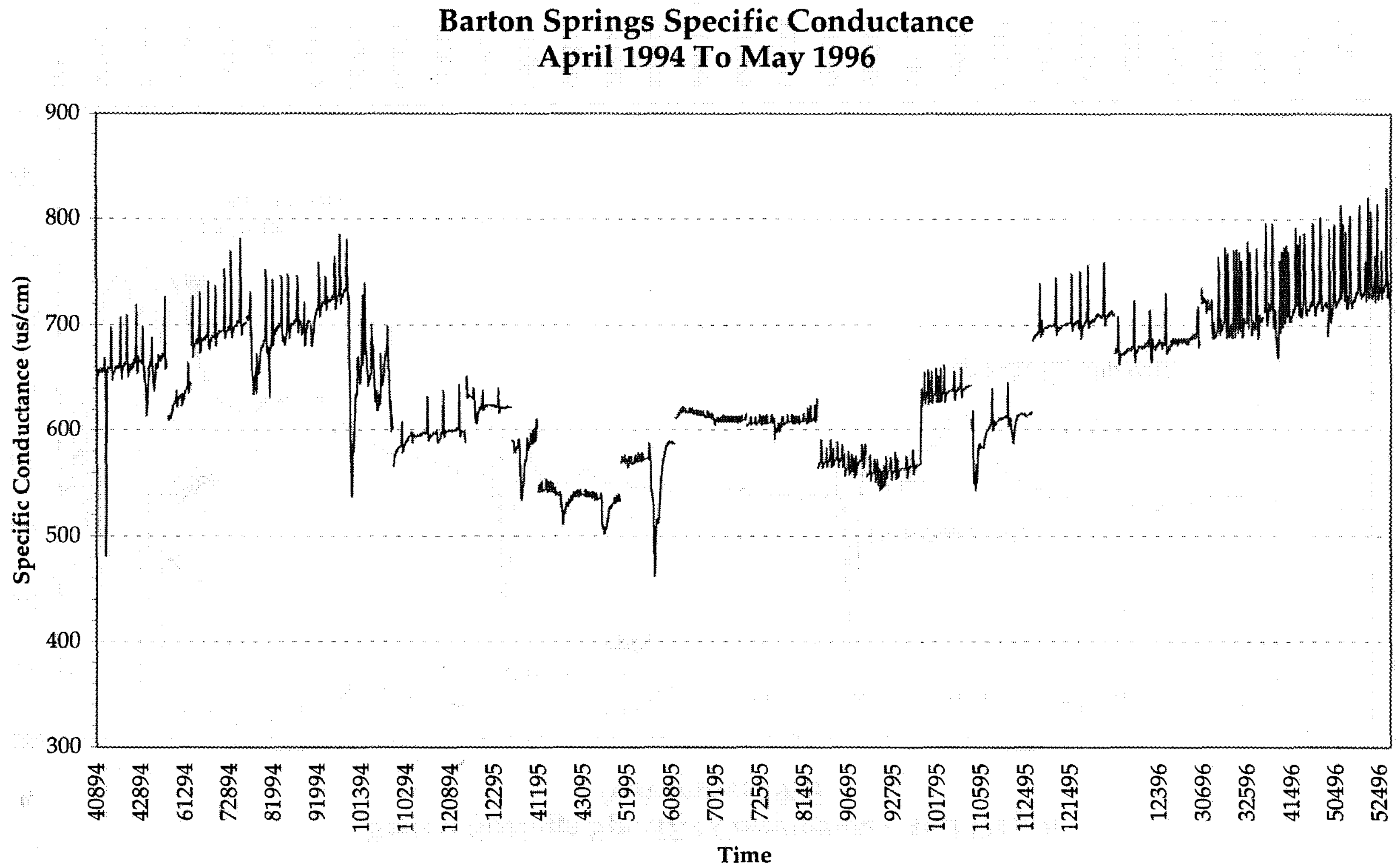
Figure 2.19

Barton Springs Specific Conductance and Depth
November 1995



Source:COA/DUD Database

Figure 2.20



Source:COA/DUD Database

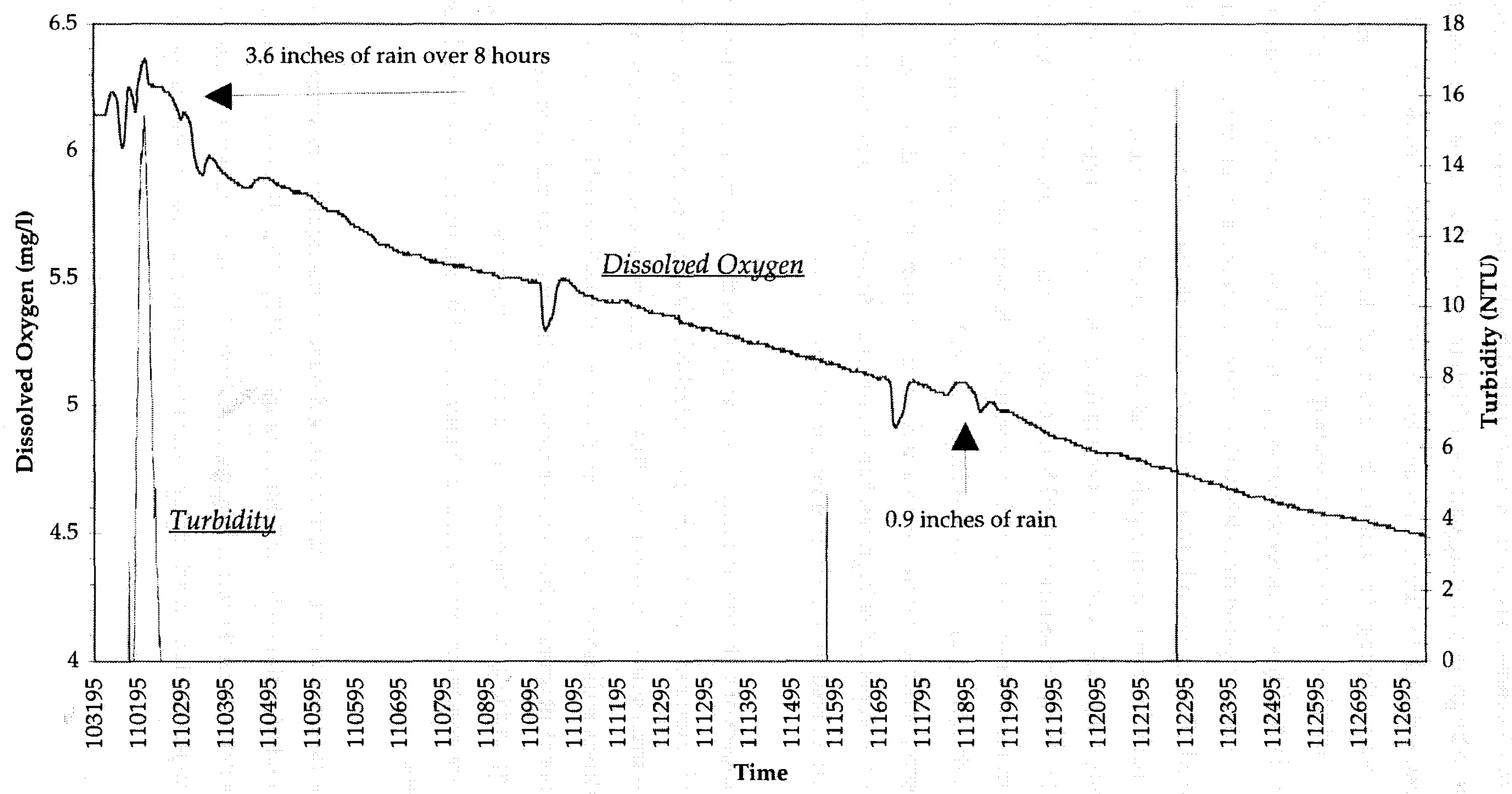
Figure 2.21 shows a typical record of turbidity and dissolved oxygen. Dissolved oxygen (DO) tends to be greatest during periods of high recharge when large volumes of well oxygenated surface waters enter the aquifer and lowest when recharge is minimal and spring discharge is low. Notice the regular shallow troughs in DO that correlate with lowering water levels in the pool. Turbidity in the springs is usually very low, below one NTU (nephelometric turbidity unit). Turbidity will increase following rains when runoff carries sediment into the aquifer and to the springs. Spring turbidity will sometimes increase when the pool water level is being lowered. During periods with low to moderate rainfall events (especially droughts) sediment may locally accumulate in aquifer conduits as runoff washes loose dirt and soil into recharge openings but lacks sufficient energy to flush sediment through the aquifer system. This effectively stores sediment until heavier rains increase recharge rates and raise water levels in the aquifer to flush sediment from conduits. The very low turbidity in the spring of 1996 is probably related to a number of factors, including: very low discharge velocities, even with dropping water levels in the pool; lack of heavy rains to mobilize surface sediment, and perhaps a prolonged period of high discharge velocities during spring and summer of 1995 which may have mobilized most sediment near the spring outlet.

This aspect of sediment loading and discharge in the aquifer may mimic conditions when urbanization increases in recharge watersheds. Increasing impervious cover will generate runoff from smaller rain events. This could increase sediment washoff and instream erosion, depositing sediment in the aquifer. Heavier rains will probably still flush out accumulated sediment but urbanization may increase the frequency of high turbidity events in Barton Springs and in general increase the TSS load to the pool. Such dynamic responses are obvious from short-term intensive data, but they cannot be simulated by currently available aquifer models.

A discussion of the characteristics of sediment in the aquifer, transport, and contaminant potential of sediment is available in Mahler (1997). This dissertation concluded that sediment discharging from Barton Springs is a mixture of surface derived and aquifer derived sediment. The suspended load discharging from the springs included fibers and glass.

Figure 2.21

Barton Springs Dissolved Oxygen and Turbidity
November 1995



Source:COA/DUD Database

Figure 2.22 shows a record of temperature and pH during a typical month. Temperature tends to be relatively constant, around 21 to 21.5 degrees Centigrade, but will change a degree or two following rainy periods during winter or summer in response to recharge of large volumes of unusually cold or warm water (when atmospheric temperatures are at extremes). This can be seen in Figure 2.23 by temperature approaching 22 degrees C in May and June of 1994 following extensive rain. This is also shown by temperatures near 19 degrees C in December 1994 and January 1995. Temperature also dips slightly corresponding to drops in pool water levels. In addition, pH is relatively constant, and the chart shows instrument drift common for pH. Typically, pH is not always affected by rain events but can change following large rain events.

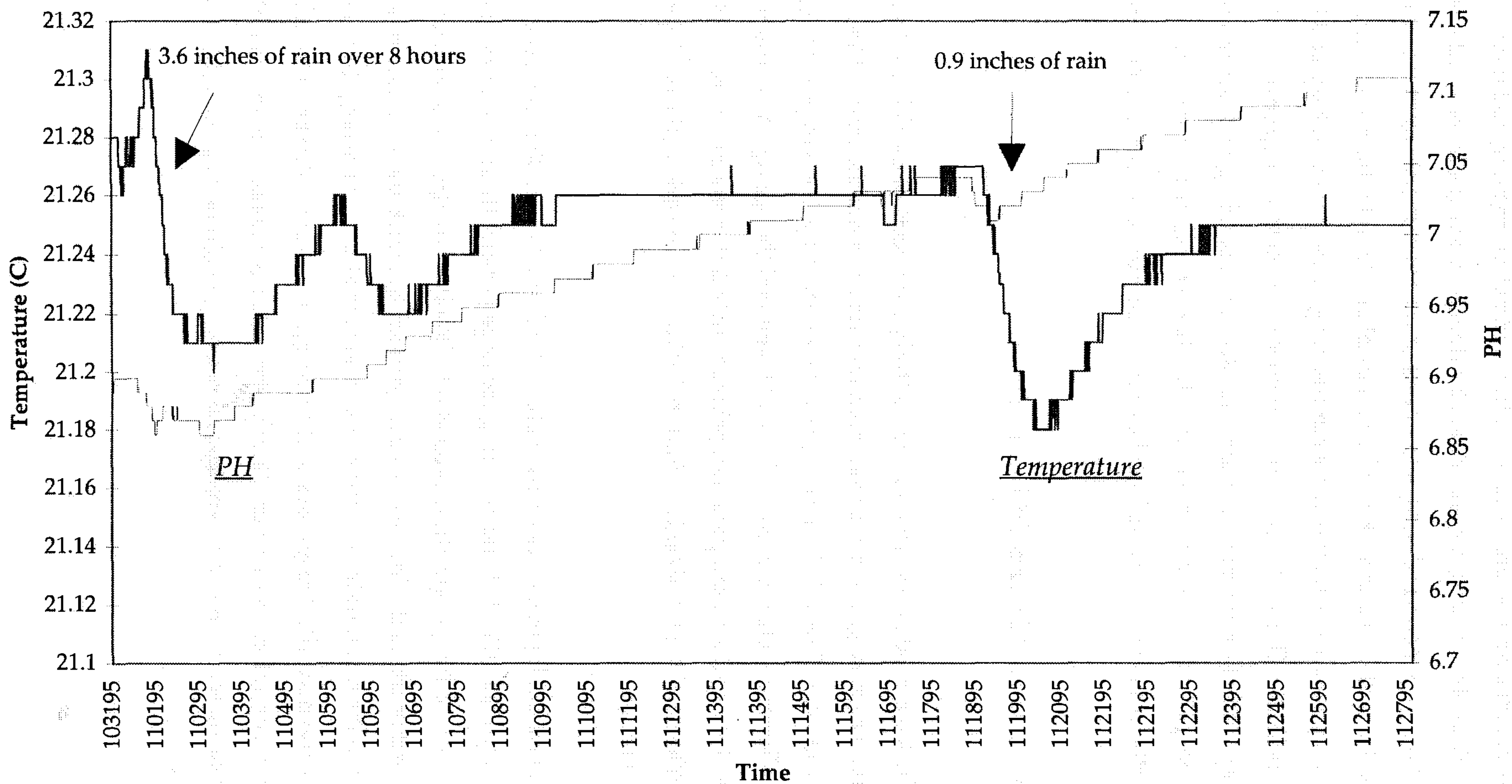
2.5.1.4 Transient Impacts Of Rain Events

The COA has made numerous efforts to study the effects of rainfall on Barton Springs water quality. The springs have been sampled for bacteria since the early 1980s, following rains of 1 inch or greater. The USGS, in cooperation with the City, has sampled the springs for several days following recharge events. The COA sampled the springs daily following two rains in the 1980's. City staff also sampled the springs hourly following two rains in 1992 and 1993. Deployment of the DataSonde in Barton Springs has recorded effects of numerous rain events on the springs.

DataSonde deployment has vastly increased information on the impacts of rain and recharge on Barton Springs. Rainfall and resulting recharge potentially affects all the parameters on the DataSonde, although specific conductance, dissolved oxygen, turbidity, and temperature are most readily affected. The degree or magnitude to which these parameters are affected is related to the magnitude of rainfall. Large events tend to have large impacts. Several other factors also may affect responses in the springs, including intensity of rainfall, antecedent soil moisture conditions, antecedent flow in the recharge creeks (existing base flow may dilute and buffer storm water impacts), and spring discharge volume (also possibly buffering storm water effects).

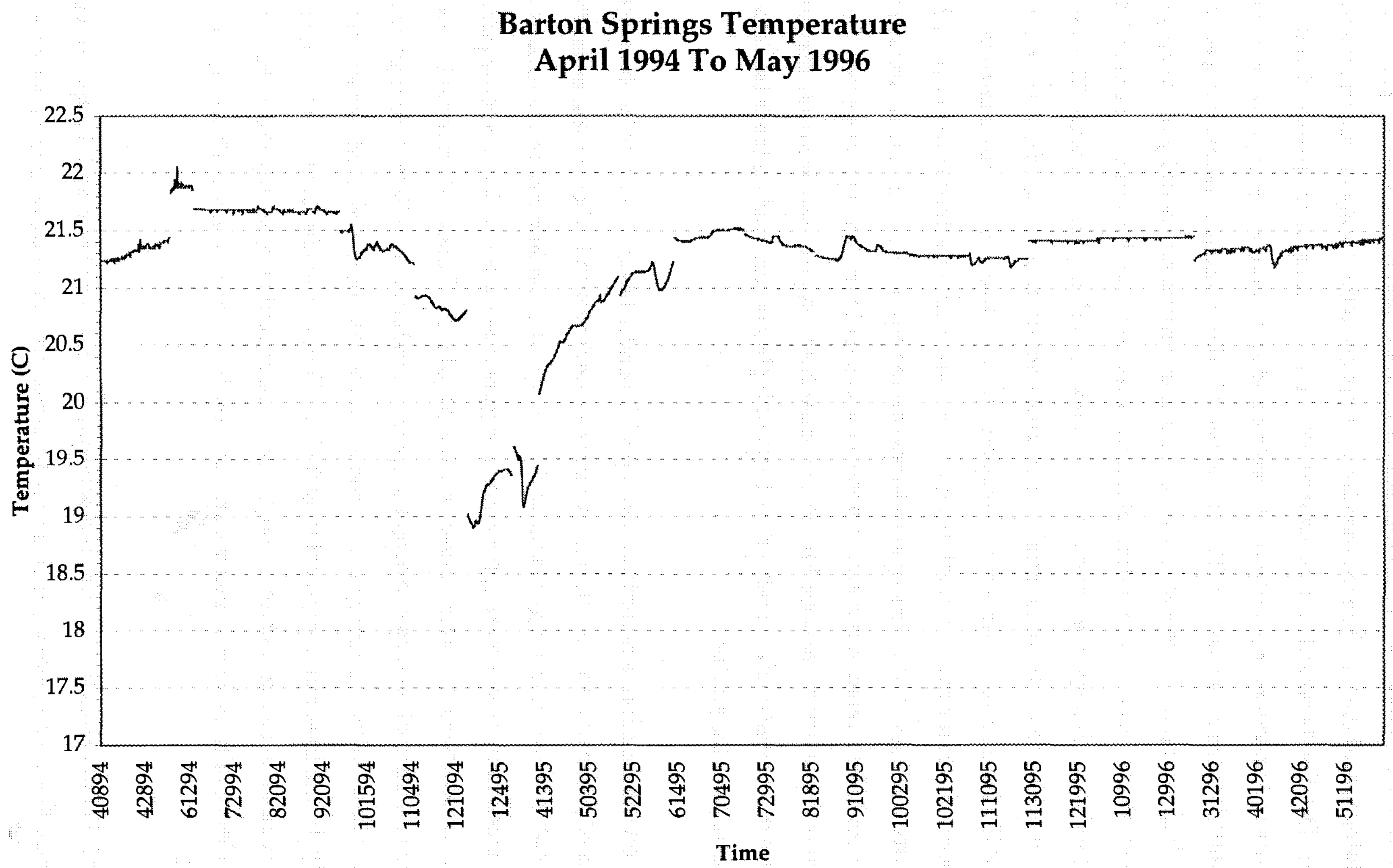
Figure 2.22

Barton Springs Temperature and PH
November 1995



Source:COA/DUD Database

Figure 2.23



Source:COA/DUD Database

The basic water chemistry measurements and responses to rain events recorded by the DataSonde are valuable in both understanding basic characteristics of the springs as well as providing more baseline data for monitoring impacts to the springs from urbanization in the future. DataSonde records can be used to determine the relative frequency, duration, and intensity of impacts as measured by its probes and also cumulative impacts. For example, turbidity data (as a measure of TSS) can be used in the future to evaluate changes in sediment loads discharging from the springs to determine if construction activity or stream erosion increases the intensity and duration of turbidity incidents in the springs. Section 2.4 of this report indicates that specific conductance is higher in urban ground water. This information can be used in the future to determine if specific conductance in the springs is higher under similar discharge rates. Temperature may also be used to evaluate future impacts. Temperature of stormwater runoff from impervious surfaces is higher than runoff from vegetated surfaces. Future changes in temperature responses in the springs following rain events could be related to increasing impervious cover in the spring watershed. Dissolved oxygen is important for aquatic life. Future dissolved oxygen measurements may indicate declines in DO that could be related to decay of higher organic debris loads in recharging creeks and perhaps in the aquifer.

Based on the DataSonde records to date, specific conductance appears to be the most sensitive measured parameter that is affected by rainfall. Andrews and others (1984) noted the relationship between recharge events and lower specific conductance in the springs from less mineralized rain water entering the aquifer. Figure 2.24 shows typical response patterns of specific conductance following different amounts of rain. DataSonde records indicate that rains of even one-third of an inch can drop the specific conductance in Barton Springs by five to 10 us/cm. Small rains impacting specific conductance have occurred in winter and summer but usually during lower discharge volumes (below 55 cfs). The effects of small rains on specific conductance can be masked by chemistry changes caused by lowering the water level in the pool. Heavy rains have dropped the specific conductance as much as 85 us/cm over a short period.

Figure 2.25 illustrates the relationship between the amount of rain and the specific conductance response. Geometric, exponential, and polynomial equations were used in regression of this data. A second order polynomial equation produces the best fit to the data but not greatly over a linear equation (R^2 of 0.5409 vs. 0.5066). A stronger relationship may be possible by grouping data collected under similar conditions, accounting for creek flow, spring discharge, and antecedent moisture.

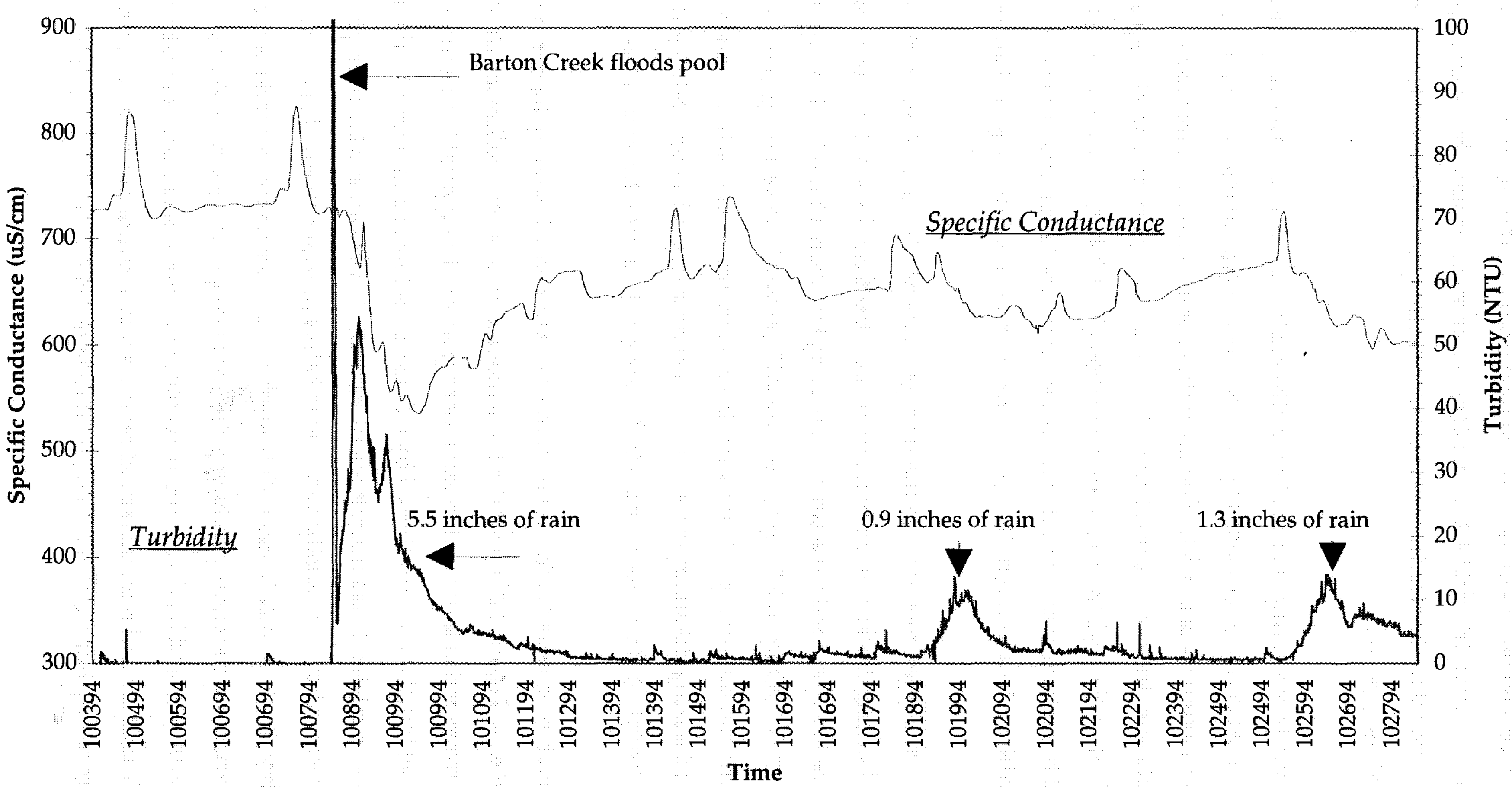
Turbidity in the springs is not always affected by rain events. This may be due to the buffering factors previously discussed. Figure 2.24 shows a typical response pattern of turbidity to different amounts of rainfall. The magnitude of the turbidity response is also related to the magnitude of the rain event (Figure 2.26). A second order polynomial equation provides the best R^2 but only slightly over a liner equation (R^2 of 0.9002 vs. 0.8549). Calibration of the turbidity probe is complicated and consequently the lower sensitivity of the DataSonde may vary with each calibration. The probe may not always detect slight changes in turbidity.

Dissolved oxygen measured in the springs is affected by rainfall and recharge because water in the recharging creeks is usually more oxygenated than the aquifer water. Short term effects on dissolved oxygen tend to be small, increasing less than 0.1 mg/L. Rains greater than one inch can increase DO up to 2.5 mg/L. Figure 2.27 shows dissolved oxygen response following different amounts of rain. There have been a few rain events which lowered DO. These have occurred during the summer months and are probably related to the slightly higher temperatures in the surface creeks and atmosphere during these months.

Temperature is usually affected by rain events but with a slightly longer lag-time than other parameters. Figure 2.27 illustrates the temperature response following different amounts of rain (arrows indicate general location of response). The typical temperature signature following rain is an initial increase followed by a decrease below pre-rain levels. The magnitude of decrease is related to the magnitude of rainfall. However, in May through September, the temperature does not usually decrease to below pre-rain levels. These characteristics are probably due to a combination of atmospheric and terrestrial conditions (i.e. lower altitudes and land surfaces are warmer producing the initial temperature increase). As rain continues, the lower altitudes and land surfaces are cooled somewhat and there is greater influence of higher altitude cool air and rain, thereby allowing a temperature decrease. Temperature of the rain is not sufficiently buffered by cool high altitude temperatures during summer months. The fact

Figure 2.24

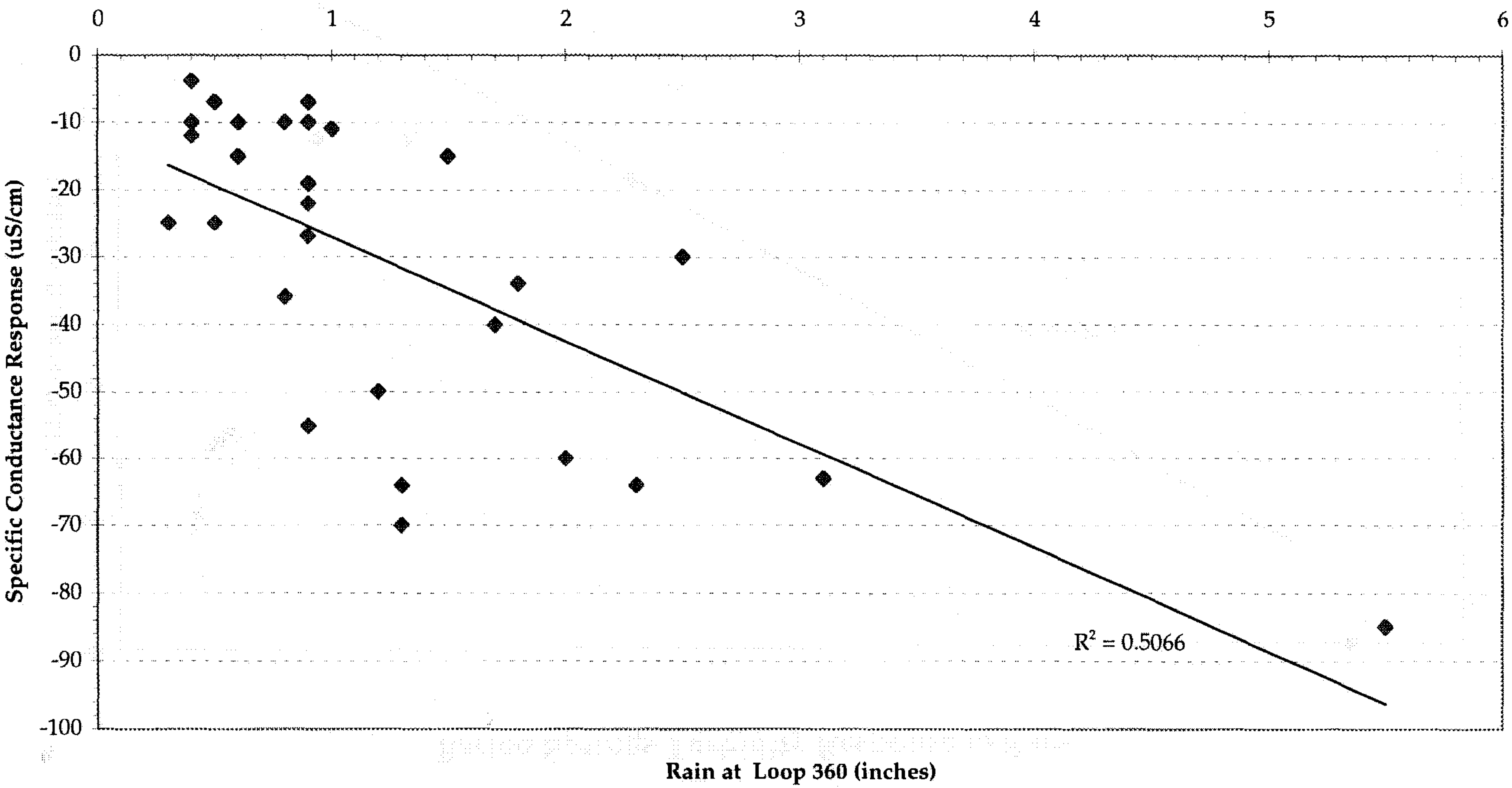
Barton Springs Specific Conductance and Turbidity
October 1994



Source: COA/DUD Database

Figure 2.25

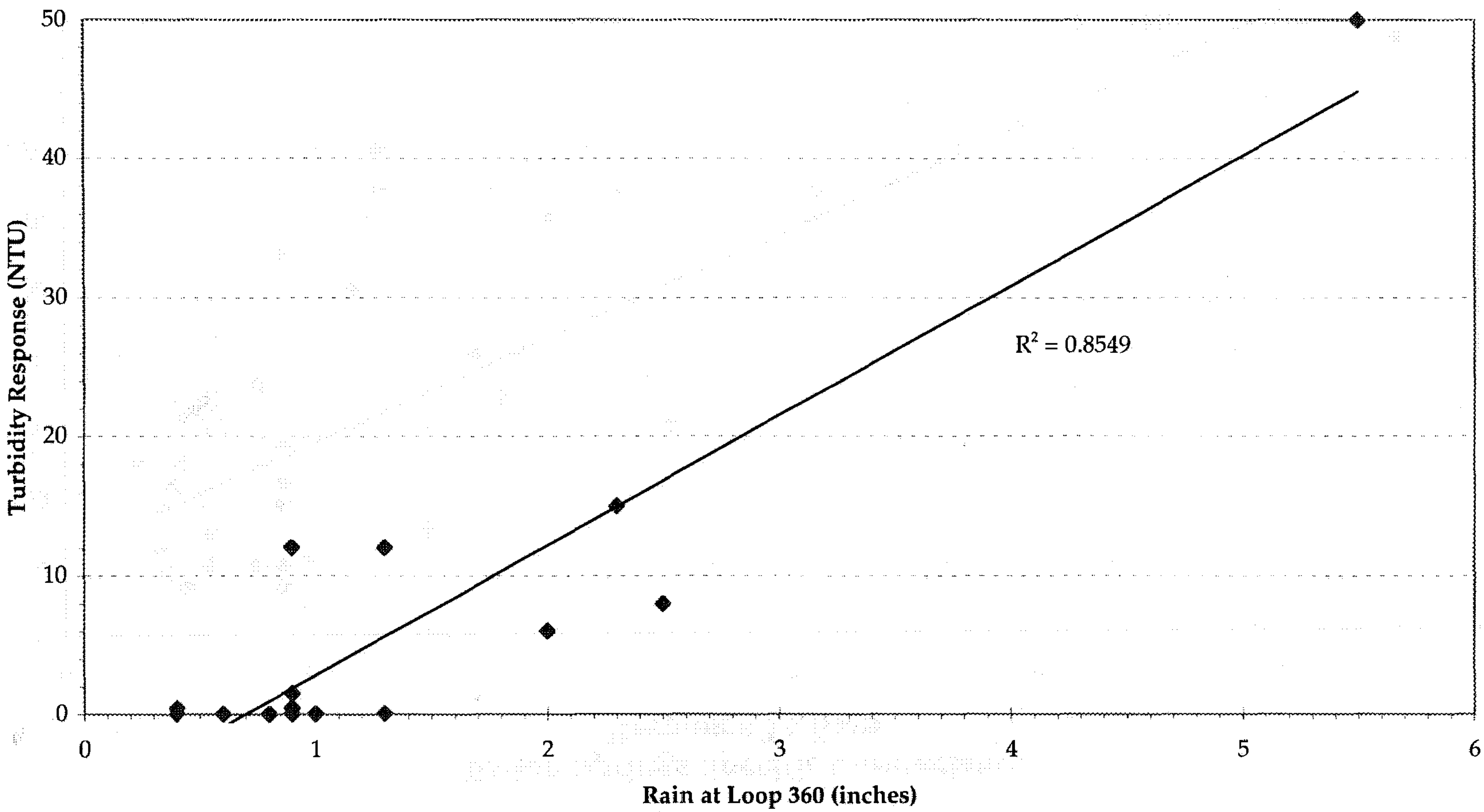
Barton Springs Specific Conductance Response To Rain



Source: COA/DUD Database 1993-1996

Figure 2.26

Barton Springs Turbidity Response to Rain



Source: COA/DUD Database 1993-1996

that temperature rises in the springs following even winter rains is surprising. This may be due to relatively warm land surface temperatures actually warming runoff and recharge water as it passes from uplands to creek channels to aquifer to springs.

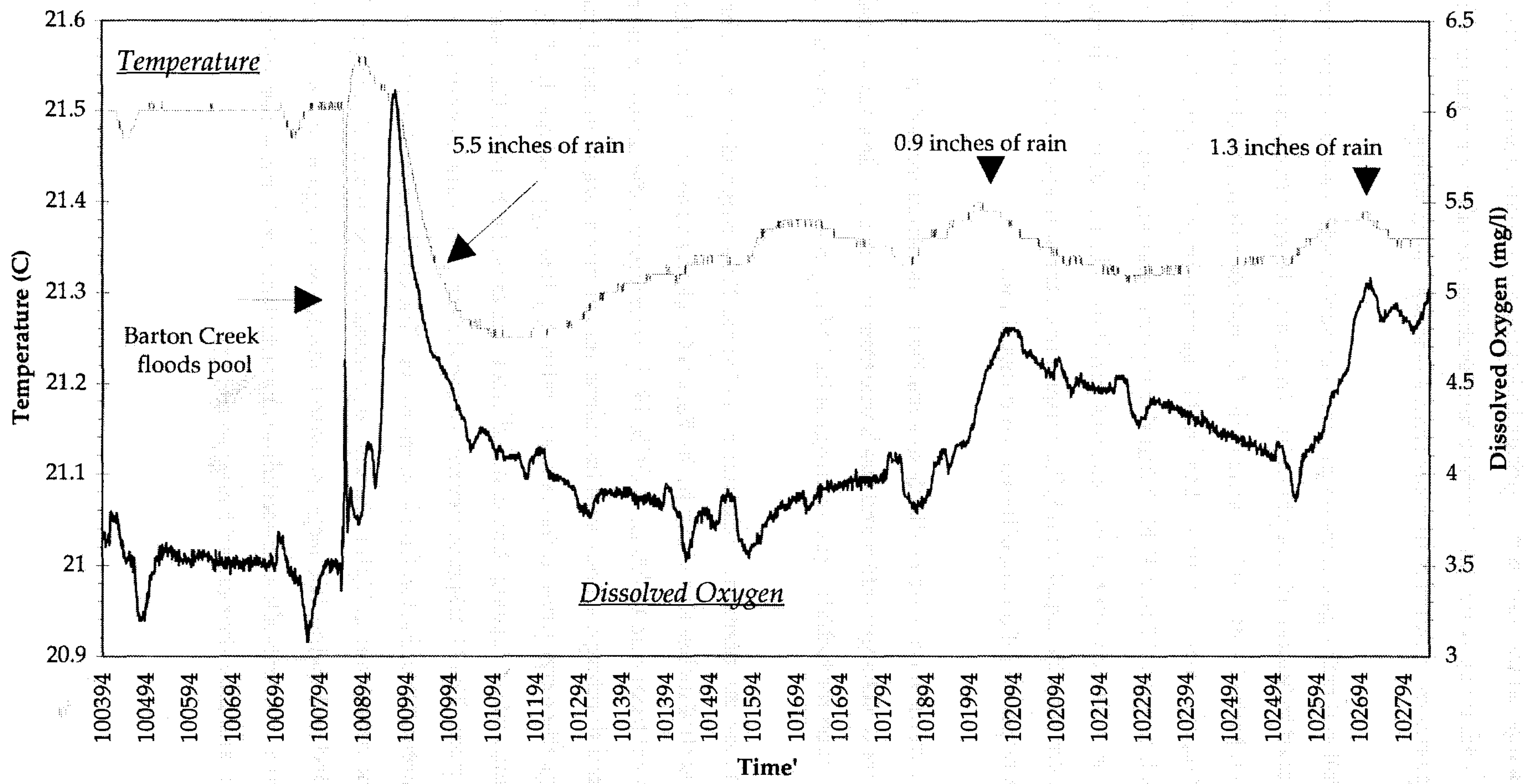
Rainfall and recharge effects on pH are very subtle, with changes from even large events measured in hundredths of pH units. There may be too little contrast between the pH of rainfall, surface water, and spring water to produce a dramatic change or the buffering capacity of the aquifer may be sufficient to limit large shifts in pH. The pH of surface water in Barton Creek is around 7.8 (see Table 3.2 in this report), whereas spring pH is around 7.0 so the drops in pH associated with rain events must result from large volumes of slightly more acidic rain water entering the aquifer and discharging from the springs. Figure 2.28 shows the magnitude of pH response following different amounts of rain.

Little historical data are available to examine the potential for reduction of contaminants which enter with recharge waters and discharge from the springs. In a single case, determining attenuation for turbidity (as a surrogate for TSS) by the aquifer was possible.

In this case, an intense thunderstorm in October 1994 dropped over 2 inches of rain at Loop 360 and nearly 4 inches elsewhere in the Barton Creek Watershed. Flow in Barton Creek quickly increased from zero to 790 cfs (USGS, 1995), overtopping the upstream dam at Barton Springs Pool and flooding the pool with turbulent muddy storm water runoff (Figure 2.24). Barton Springs discharge prior to the rain was relatively low, approximately 25 cfs. The combination of flooding and low spring flow enabled creek storm water to reach the DataSonde at the bottom of the pool. The DataSonde recorded a rapid change in water chemistry indicating measurements of Barton Creek storm water. The creek water characteristics included low specific conductance, high turbidity, high dissolved oxygen, and high pH. As flooding subsided and spring discharge increased, aquifer water again flowed across the probe. This sequence of events allowed recording characteristics of storm water which both recharged the aquifer and later discharged from the springs.

Figure 2.27

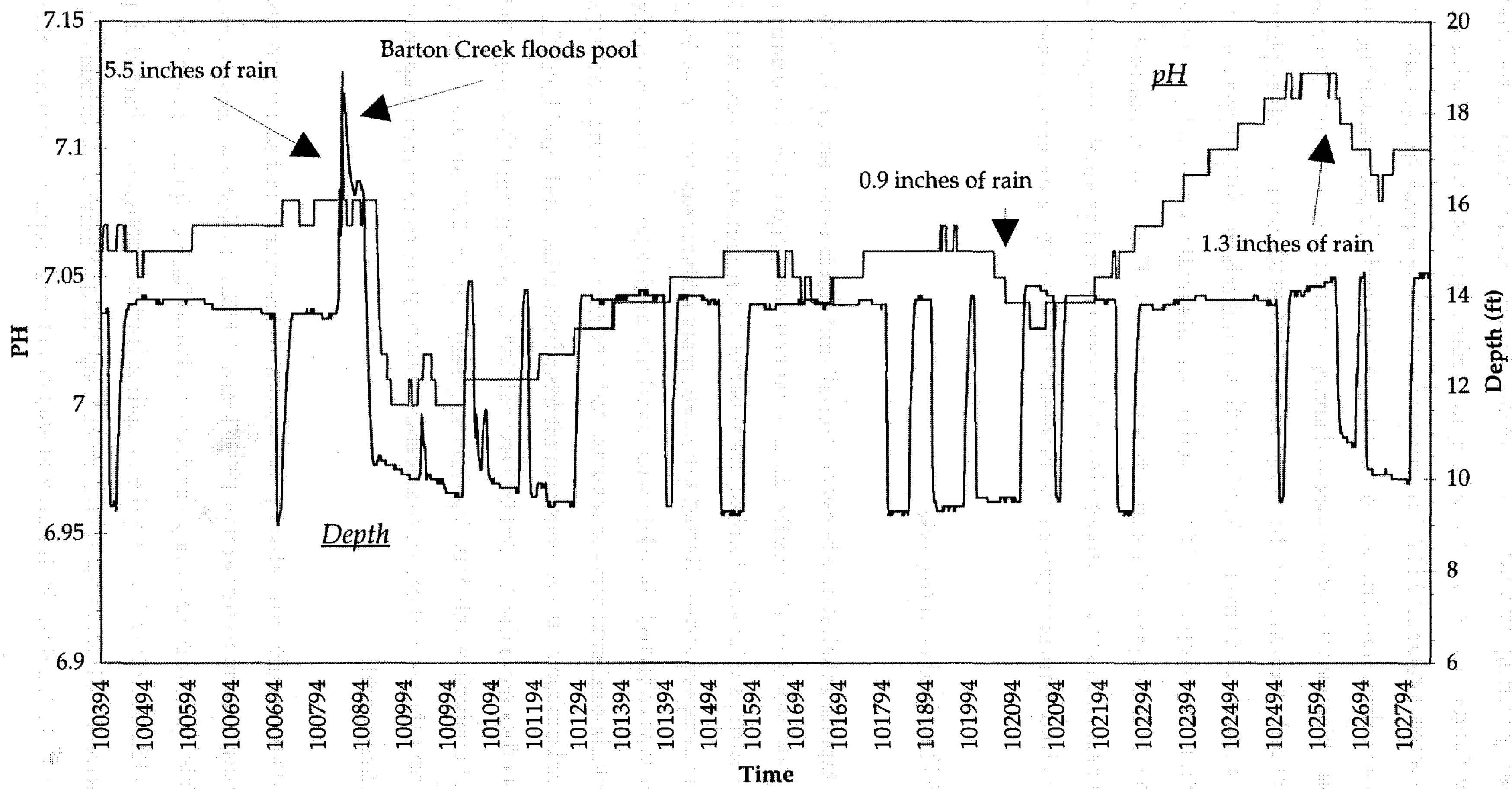
Barton Springs Dissolved Oxygen and Temperature
October 1994



Source: COA/DUD Database

Figure 2.28

**Barton Springs Depth and PH
October 1994**



Sourse:COA/DUD Database

Turbidity during the October 1994 event was analyzed to estimate the amount of attenuation TSS undergoes in the aquifer during and following a rain event. Turbidity values in the creek storm water averaged 180 NTUs compared to average peak spring turbidity of 49 NTUs. Based on these values turbidity was reduced approximately 73 percent during passage through the aquifer. Since most storm water and spring turbidity is caused by suspended solids, a 73 percent reduction implies that large amounts of solids drop out of suspension and are deposited in the aquifer. Data from 1981-82 (Andrews and others, 1984) suggest even greater TSS reduction, approximately 95%, based on samples collected from Loop 360 and Barton Springs. The fate of the deposited sediments is not known. They may be remobilized during succeeding storm events, much as sediment in creek channels, and gradually migrate to a discharge point or be in long term storage only to be re-suspended during exceptional events.

2.5.1.5 Timing of Rain Impacts

The temporal relationship between rainfall and storm water effects in Barton Springs have not been understood until recently. In fact, several years ago when the primary closing criterion for Barton Springs Pool was fecal coliform bacteria concentrations in excess of 200 colonies/100 ml, bacteria samples were collected following rains without regard to how long after the rain the sample was collected. No data were available to give pool managers an idea of how long it took for bacteria concentrations to increase following a rain. Knowing that bacteria concentrations increase because of storm water runoff from both urban and rural land, COA staff examined bacteria data from the ATCHHSD and rainfall data from the FEWS from 1986 to 1992 to provide the first analysis of this time lag (Johns, 1994b). Figure 2.29 illustrates the results of this effort. The figure shows that bacteria concentrations first begin to increase approximately 11 hours following rainfall.

Preliminary results indicated by the historical data were verified by intensive sampling following a storm in November 1992 (Johns, 1994b). In this case, more specific information was available on flow conditions in Barton Creek and Barton Springs as well as the effects on other parameters monitored during the sampling. Barton Springs was discharging approximately 102 cfs, Barton Creek was flowing 6.2 cfs at Loop 360 and there was no rain greater than 0.08" for six days prior to the three inch rain that was monitored. Figure 2.30 shows that a decrease in specific conductance coincided with an increase in fecal coliform, indicating that the storm water was discharging from the springs 14 hours following the rain. Turbidity (Figure 2.31) also spiked at 14 hours, but turbidity began gradually to increase well before the spike at 14 hours.

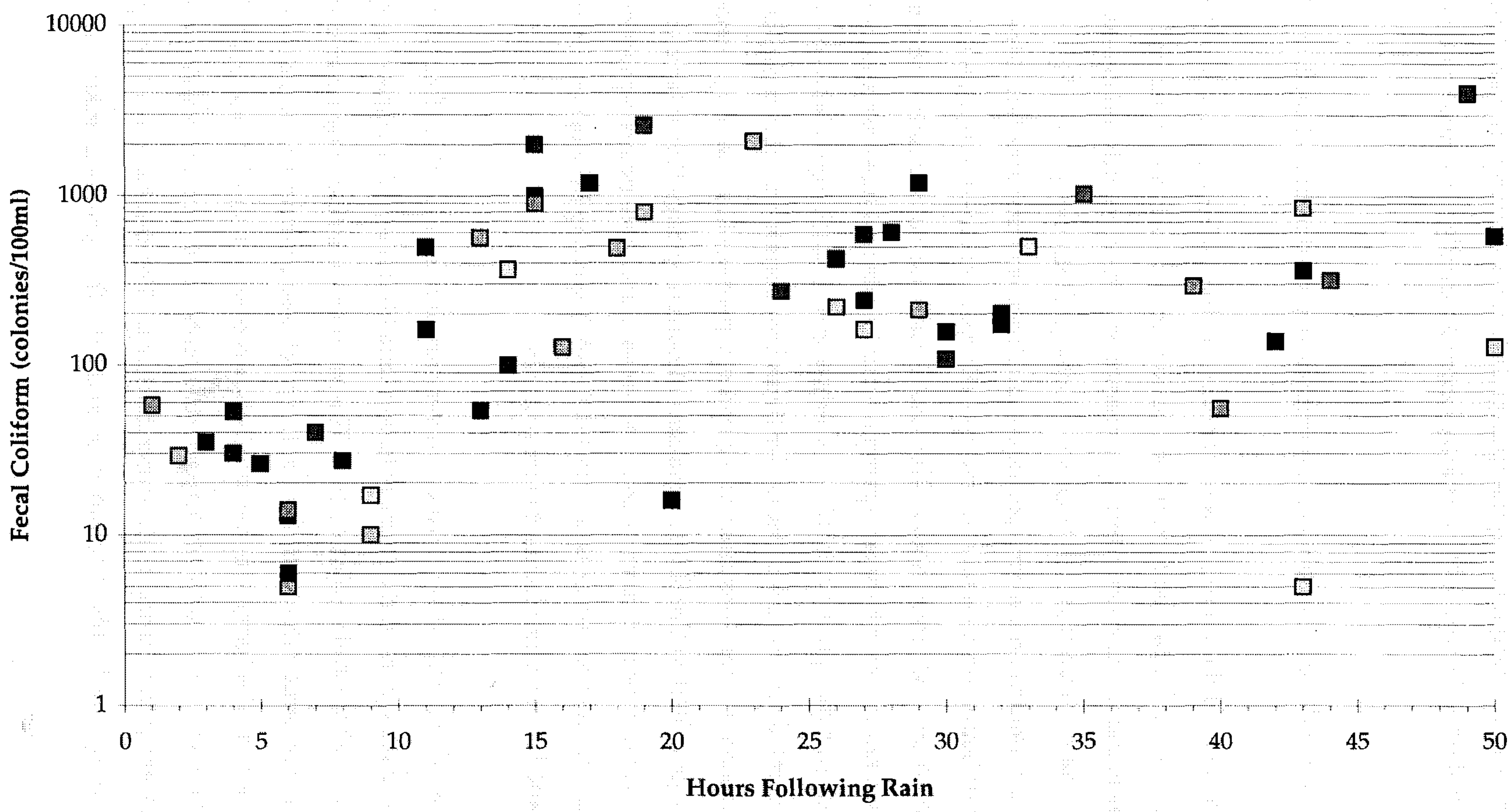
Additional discussion on this characteristic is provided in Section 2.5.6 of this report.

Refinement of the timing of rainfall effects on Barton Springs can be determined by using closely spaced data points from DataSonde records and rainfall records from the FEWS rain gages in the springs' contributing watersheds. These records indicate when rain begins and when runoff from that rain begins to discharge from the springs. Figure 2.32 shows the time between rainfall and when specific conductance was first affected. Most data indicate a lag of over 10 hours between rainfall and specific conductance effects, however a few data points plot between five and seven hours. The source and cause of the early responses is unknown. A specific relationship between spring discharge rate and these early rainfall effects was not identified although they do all occur when spring discharge is between 40 and 60 cfs. Many later rainfall effects also occur under these flow conditions. It is possible these data points result from recharge more proximal to the springs, perhaps in a tributary. Another possibility is recharge in Barton Creek just upstream of Barton Springs Pool where urbanized tributaries allow rapid runoff of storm water. However, a few data points representing early rainfall impacts to the pool occur when Barton Creek is gaining flow upstream of the pool, suggesting that another recharge location is more likely.

DataSonde records also indicate that very small rains also affect Barton Springs. Some rains between 0.2 inches and 0.5 inches have a small but noticeable impact on spring chemistry, whereas other similar rains do not. The main factor influencing these impacts appears to be spring discharge rates, with flow at Loop 360 also playing a role. Rains affected the springs when spring discharge was below 55 cfs and flow at Loop 360 was zero. Rains that did not affect the springs usually occurred at discharge rates over 68 cfs with Loop 360 flow not a significant factor during high spring discharge. The mechanism allowing small rains generating runoff only in urban areas to impact the springs is unknown. One possibility is a

Figure 2.29

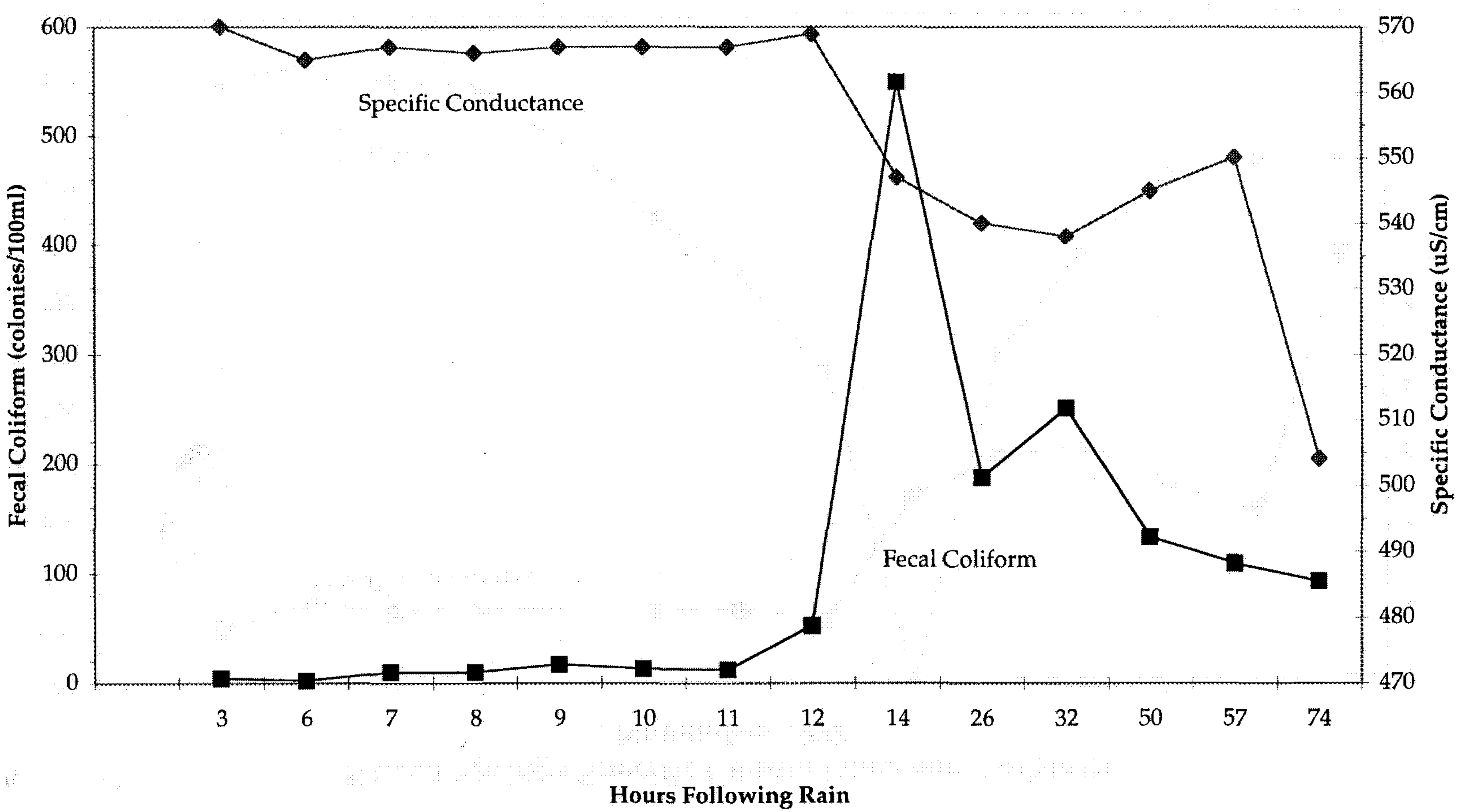
Timing of Fecal Coliform Effects In Barton Springs Following Rain



Source:COA/ATCHD Database, 11/86-7/92

Figure 2.30

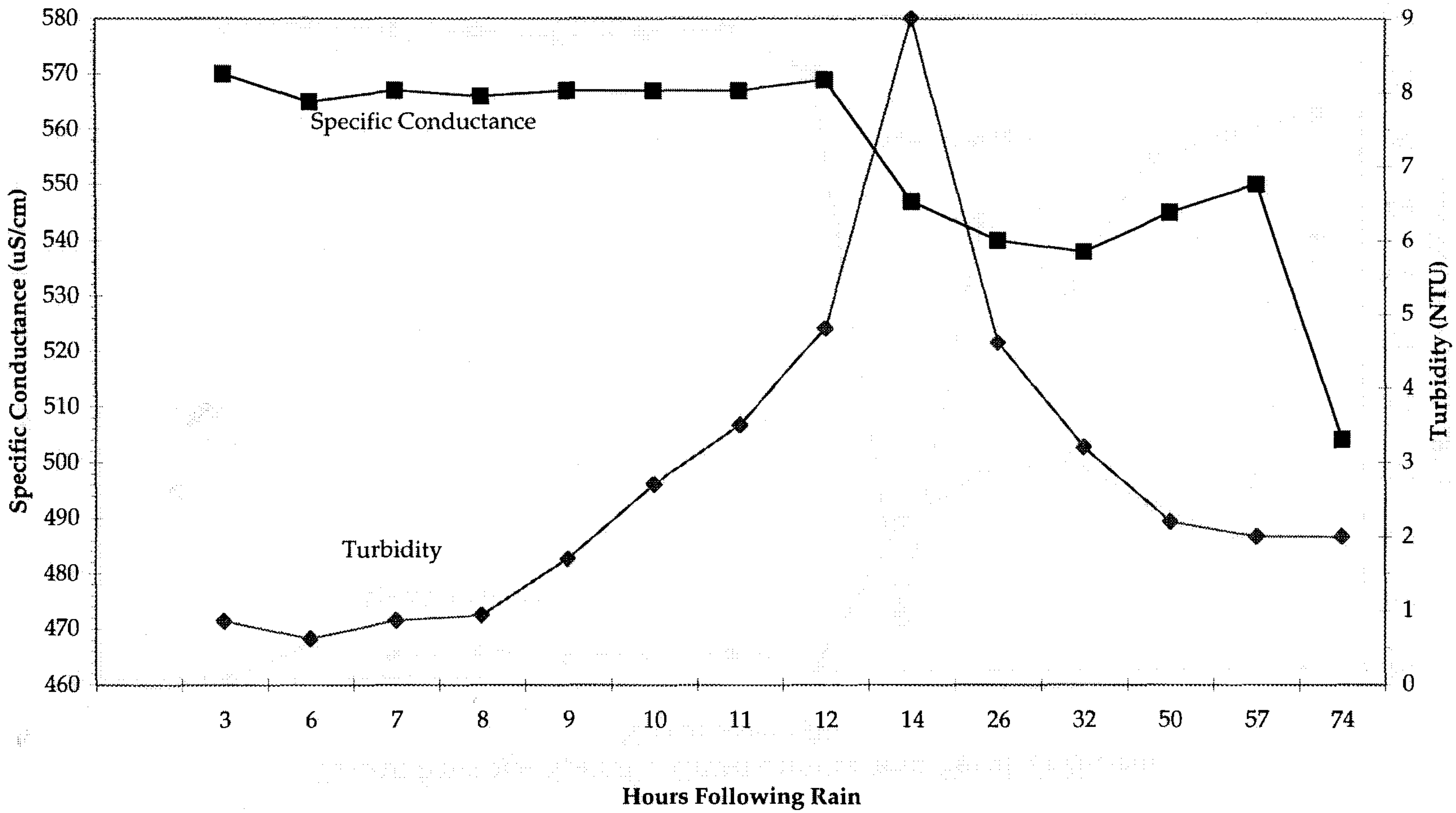
Barton Springs Specific Conductance and Fecal Coliform
November 1992



Source:COA/DUD Database

Figure 2.31

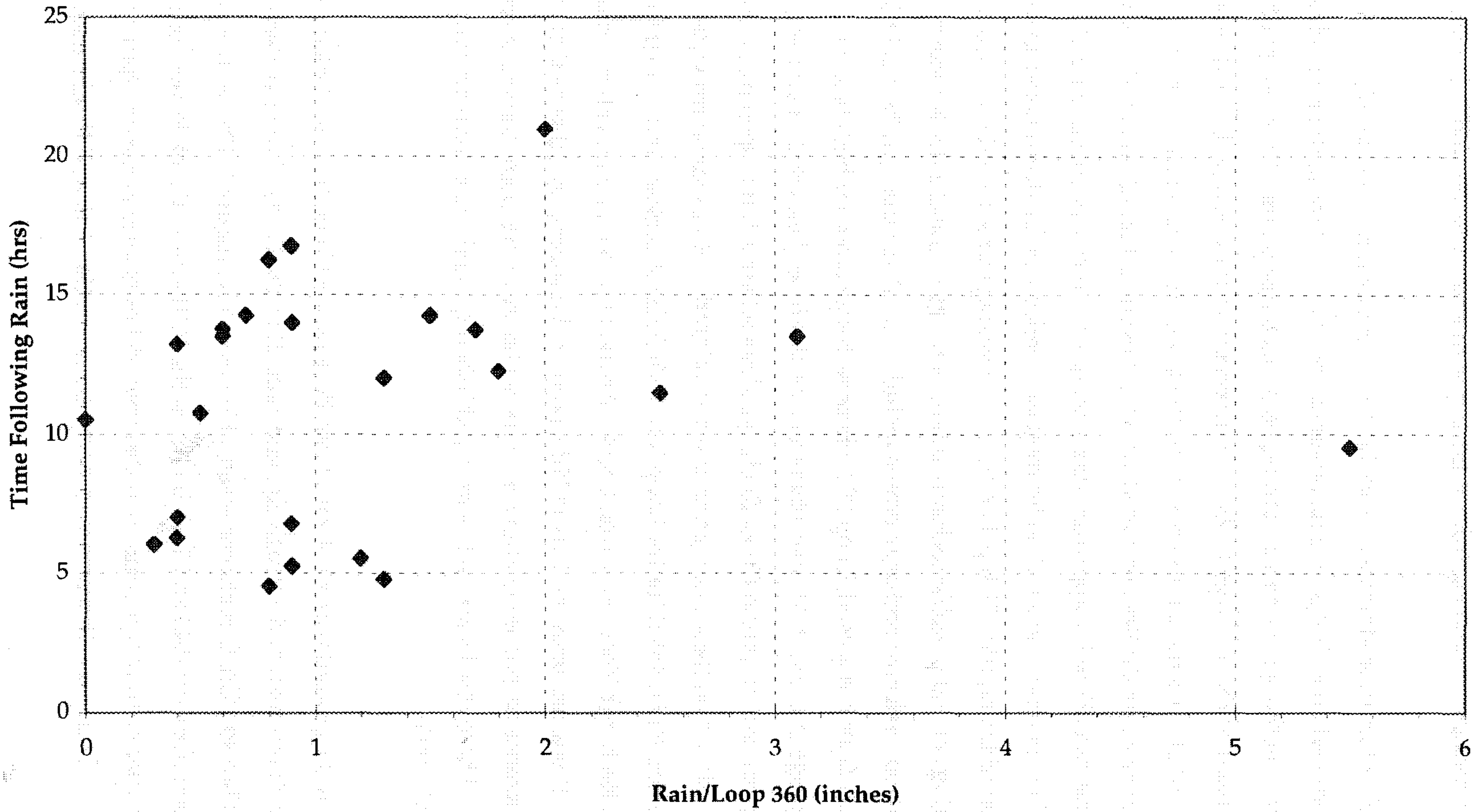
Barton Springs Specific Conductance and Turbidity
November 1992



Source:COA/DUD Database

Figure 2.32

Barton Springs Specific Conductance Response Time Following Rain



Source:COA/DUD Database 1993-1996

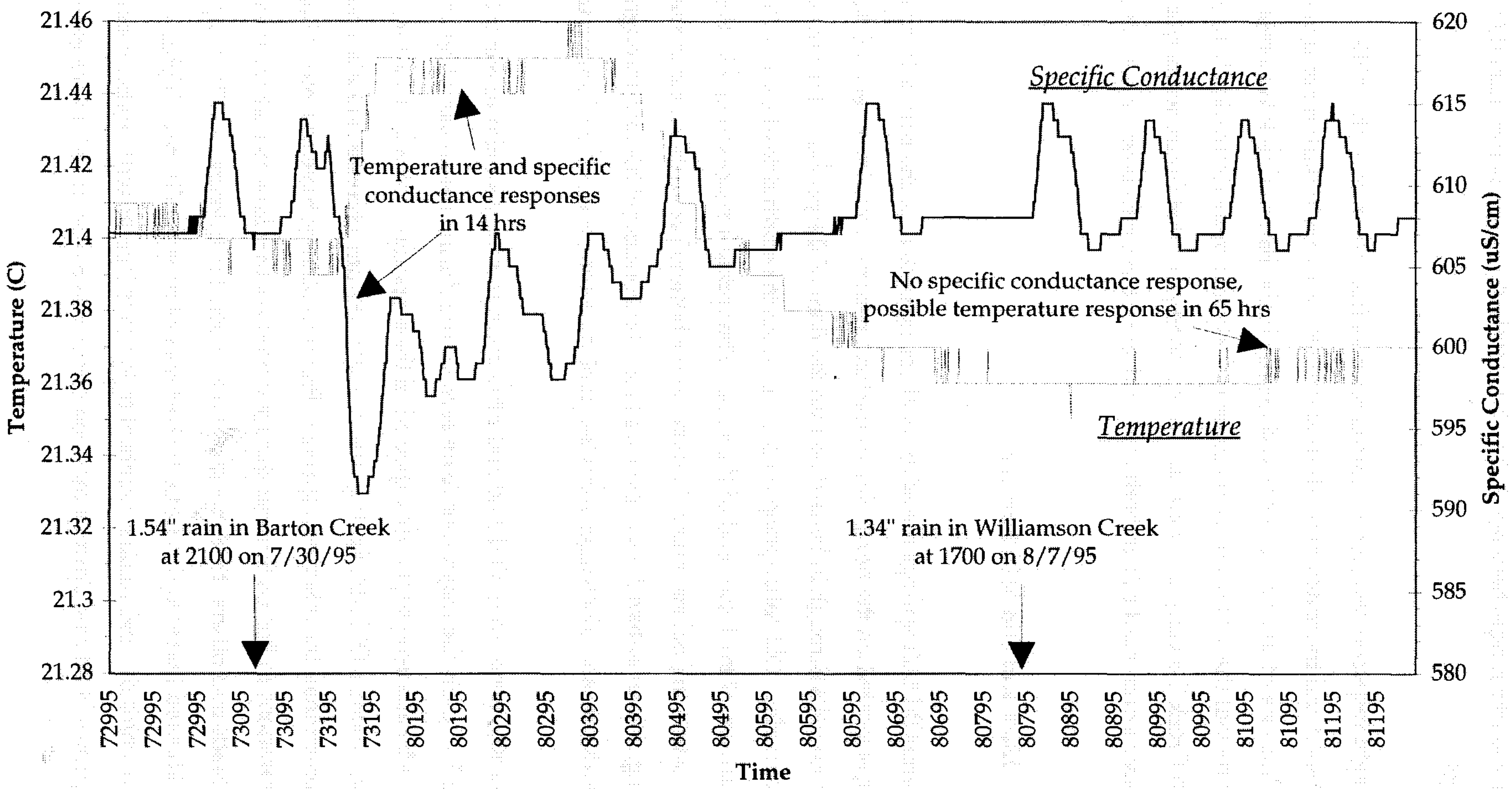
perched flow conduit in which recharge waters enter, perhaps only in a certain area, that leads to the springs without significant mixing with aquifer water until very near the springs.

Travel velocity for storm water in the northern portion of the aquifer can be estimated by knowing when recharge begins (assumed at 1/4 - 1/2" rain), the time when impacts are first detected in the spring and assuming likely recharge points. Previous studies have shown that 85 percent of the recharge to the aquifer occurs in the creek beds (Andrews and others, 1984). Previous studies have also shown the creek reaches where large volumes of recharge occur. These previous studies combined with field examination of potential or known recharge features can allow for approximations on specific recharge locations to determine at least "ball park" estimates on ground water migration velocities for storm water in the northern-most section of the aquifer. Using 14 hours as an average time for rain to impact the springs and selecting several possible recharge points, a range of travel rates for storm water can be estimated. Selected recharge points include a small tributary in Barton Hills where the Barton Springs fault is exposed, Loop 360 where recharge rates are high based on USGS studies and a rain gauge is present, MoPac where a large sinkhole (Jones Sink, Hauwert, 1995) is present, and the upper end of Barton Creek Recharge Zone where a Karst opening is visible in the bed of the creek. Based on these sites, ground water migration times for storm water vary from 330 ft/hr for Barton Hills, 855 ft/hr for Loop 360, 1070 ft/hr at MoPac, and 1215 ft/hr for the upper end of the Recharge Zone on Barton Creek. An average velocity for estimates from all sites is 867 ft/hr. If one assumes the Barton Hills point is the source of recharge that causes the specific conductance responses in about 6 hours, water from this point travels at approximately 660 ft/hr. These results are well within published ground water velocity ranges for Karst aquifers (ASTM, 1995).

Estimating ground water velocity from Williamson Creek is more difficult because rain rarely falls in this watershed exclusively, and rainfall in the Barton Creek Watershed obscures impacts of Williamson Creek recharge water. However, on August 7, 1995 a summer thunderstorm dumped between 0.43 and 1.34 inches in the Williamson Creek Watershed exclusively. A very subtle change in temperature was detected 65 hours later in Barton Springs (Figure 2.33). Using this travel time and theoretical recharge points at Oak Hill and Brodie Lane generates ground

Figure 2.33

Barton Springs Specific Conductance And Temperature July 29-August 11, 1995



Source: COA/DUD Database

water velocity ranges between 340 and 450 ft/hr for storm water from this watershed to Barton Springs.

The slight response detected in Barton Springs from the rain in the Williamson Creek Watershed and the much more dramatic responses seen in Barton Springs from other rains, including one of similar size centered mainly in the Barton Creek Watershed on July 30, 1995, illustrate that the springs respond more quickly and more dramatically to rains and recharge in Barton Creek than any other creek. This also implies that future water quality in Barton Creek will have a dominant role in both long and short term effects on Barton Springs.

2.5.2 Eliza and Old Mill Springs

Eliza and Old Mill Springs are additional spring outlets of the Barton Springs system. Eliza Spring is located on the north side of Barton Creek near the lower end of Barton Springs pool. Water upwells through holes drilled into the floor of the pool and through cracks in the concrete sides. Old Mill Spring discharges from the south side of Barton Creek about 200 feet downstream of the lower end of the pool. The spring surfaces in an old Works Progress Administration pool structure. Rubble on the bottom prevents access to the actual spring opening. Water enters the spa pool through the bottom rubble and through terrace alluvium on the south side and discharges from the pool via a concrete culvert leading to Barton Creek.

Chemically, water from Old Mill and Eliza springs is very similar to water from Barton Springs. Figure 2.17 plots the major ions from each spring during recent sampling and indicates the calcium-bicarbonate signature expected of these springs. Eliza and Barton springs are the most similar, whereas Old Mill Springs has a larger sodium, chloride, sulfate, and potassium component than the other two springs. Previous studies have attributed higher TDS concentrations in Barton Springs during periods of low flow to leakage from the "bad water line" (Slade and others, 1986; Senger and Kreitler, 1984; Senger, 1983). Senger and Kreitler (1984) showed that samples from the bad water line typically have higher concentrations of sodium, chloride, and sulfate, identical to the constituents with higher concentrations in Old Mill Springs. Old Mill Springs may constantly discharge some bad water line water, as it is physically closer to this water zone, although other sources of sulfate are possible such as from urbanization. Ion trends through 1995 and into 1996 generally correlate low flow conditions in the aquifer with increasing concentrations of these constituents.

Since 1994, the COA has periodically collected samples from these springs to test for a comprehensive suite of parameters, including nutrients, major inorganics, and selected metals. Some tests have included pesticides, herbicides, volatile and semi-volatile organic compounds. Table 2.7 indicates the metals detected in these springs. All metal detections were in the parts per billion (ppb) range. No herbicides, pesticides, volatiles, or semi-volatiles have been detected in either spring by COA testing. The BS/EACD (Hauwert and Vickers, 1994) detected total petroleum hydrocarbon (TPH) in Old Mill during two separate collections. The first sample was collected March 16,1994, 10 hours following 0.35 inches of rain and detected 1.9 mg/L TPH. A second sample was collected under base flow conditions on April 18, 1994 and detected 1.3 mg/L TPH.

Metals commonly are identified in Old Mill Springs, including barium, iron, manganese, and strontium. Copper and nickel have been identified in single separate samples. The BS/EACD also detected several heavy metals (arsenic, copper, iron, lead, selenium, and zinc) in the March 1994 storm sample, all within the ppb range in both dissolved and total analyses. A COA sample from Old Mill September 8, 1995 16 hours following a 0.9 inch rain also detected some common metals (barium, copper, iron, manganese, and strontium) but arsenic and lead were not detected in the sample. Low bacteria concentrations during this sampling suggest that storm water either had not yet begun to discharge from the spring or had already passed through the conduit system.

Testing for metals in Eliza Spring has been conducted for fewer metals, but copper, iron, lead, and nickel have been detected (Table 2.7).

Nutrient concentrations from Old Mill and Eliza Springs (Table 2.7) differ from each other slightly. Both springs have similar nitrate-nitrogen, ammonia-nitrogen, and phosphorous concentrations under base flow conditions. No storm flow samples have been taken.

Multiprobe data loggers have been placed into Old Mill Springs three times over the past year. Equipment problems and placement location prevented collection of good data during one deployment. Deployment during November 1995 and January 1996 failed to record any rain events; however, non-storm data indicate diurnal variations in temperature and dissolved oxygen that may be attributed to solar heating of the pool water and an increase in oxygen production by algae in the pool. Additional comparisons between these springs using results of *in-situ* multiprobe data loggers is presented in Section 2.5.5 of this report.

In-situ instruments have not been used in Eliza Spring because of poor locations available for secure placement.

2.5.3 Cold Springs

Cold Springs (and associated Deep Eddy Spring) discharges along a fault in the Rollingwood area of the aquifer into Town Lake northwest of Barton Springs (Plate 1, Site 97). Senger (1983) measured water level changes coincident with dropping water levels in Barton Springs Pool and determined that this area of the aquifer was not directly connected to Barton Springs. Brune (1981) states that these springs discharge from artesian pressure, though field observations for this study do not indicate artesian discharge.

Currently, the springs discharge from limestone and river alluvium a few inches above the water level in Town Lake. Additional spring discharge occurs below the water surface of Town Lake along the slope toward the bottom of the lake as indicated by cool water temperatures relative to lake water. Discharge from the surface springs varies noticeably from wet to dry conditions. Under wet conditions, springs discharge from two primary outlets about 20 feet apart and several smaller outlets in river alluvium on either side of the primary outlets. During dry conditions, most visible discharge is from a single outlet where a small cistern detains flow and separates it from river water. Brune and Duffin (1983) reported discharge above the lake surface ranging from 2.9 to 4.2 cfs.

Piper plots of Cold Springs ions indicate calcium-bicarbonate water nearly identical to Barton Springs water (Figure 2.17), although with slightly less dissolved solids. Concentrations of major ions tend to be less than either of the other Edwards springs. A summary of nutrient data from samples collected over a similar time as other Edwards springs is shown in Table 2.7. These data indicate median concentrations of nitrate-nitrogen of 1.15 mg/L, ammonia-nitrogen 0.02 mg/L, TKN 0.16 mg/L, ortho-P 0.06 and 0.03 total P. These values tend to be less than in the other springs, except ortho-P which is higher and ammonia-nitrogen which is the same.

Parten (1991) sampled Cold Spring three times to determine if rainfall was flushing septic tank effluent to the springs. Two samples were collected approximately 8 and 9.5 hours following two different storms in the one inch range and one sample was collected following dry conditions. Parten attributed doubling of nitrate and ammonia-nitrogen concentrations to flushing during rains and a decrease in chloride to dilution. A similar response was found during COA sampling 10 hours following a one inch storm 9/20/95. However, in all these cases both fecal coliform and fecal streptococcus bacteria concentrations were low, 2 - 25 colonies/100 ml, apparently in background ranges. Based on evidence from Barton Springs where bacteria concentrations increase dramatically following rains, these Cold Springs samples do not appear to be storm water. One possibility is that these samples represent water recharged in uplands areas relatively near the springs, and that the nutrients and other constituents were leached out in the unsaturated zone.

Insufficient data exist to determine when storm water runoff discharges from Cold Springs. DataSonde deployment either missed storms, or tampering during deployment prevented data collection. COA grab samples from other Karst springs indicate that bacteria concentrations should increase in the springs. A grab sample 8/16/91 was collected 36 hours following a one inch rain and had a fecal coliform concentration of 127 colonies/100 ml. Another sample on 5/15/94 was collected 14 hours following a 0.75 inch rain and had a fecal coliform concentration of 532 colonies/100 ml; however, a 1.25 inch rain occurred 45 hours prior to sampling, making it impossible to determine which rain was affecting the spring.

2.5.4 Backdoor Spring

Backdoor Spring is located at the upper end of the Recharge Zone on Barton Creek approximately 0.7 miles downstream of the Mt. Bonnell Fault and the beginning of the Recharge Zone (Plate 1, Site 82) (see Appendix B, photo 2a). The spring discharges from the base of a thick vuggy micrite in the Dolomitic Member of the Edwards Group (member usage of Hauwert and Hanson, 1995) at the downstream end of a series of small seeps and springs below Sculptured Falls. These discharges form a rare perennial pool over the Edwards Aquifer Recharge Zone. A cave adjacent to the spring indicates a paleokarst flow conduit. Flow estimates range from 10-20 gpm (Brune and Duffin, 1983; Hauwert and Hanson, 1995) to three gpm in April 1996 following very dry conditions.

Regional Edwards ground water table elevation is far below the elevation of this spring, indicating that this is a perched water table, perhaps resting on less porous micrite in the Dolomitic Member of the Edwards. The recharge basin for this spring is largely unknown. Unpublished data from the BS/EACD indicate perched water at several sites south of Backdoor Spring extending to the Hwy 290 area. Some recharge may come from Barton Creek where it enters the Recharge Zone upstream of the spring. Veni (1988) used spring base flow volumes to calculate the size of Karst drainage basins. Using 0.1 square miles for each gallon per minute of discharge (three to 20 gpm) yields a recharge basin ranging from 0.3 to two square miles for Backdoor Spring. A ground water basin of two square miles would roughly include all the area between the spring on Barton Creek and U. S. Hwy 290.

Chemically, Backdoor Spring is similar to the other springs. Subtle differences can be seen, however, in the ion chemistry. A Piper plot of recent ion data from Edwards springs (Figure 2.17) indicates that Backdoor Spring water has slightly higher bicarbonate and lower sulfate than the other springs, plotting below the 20 percent SO4+Cl line, whereas the other springs plot above it. This is a signature associated with the more rural areas of the aquifer, as discussed in Section 2.6 of this report. Plots of Backdoor Spring ion milliequivalents on Schoeller diagrams are almost exactly the same as those for rural springs in the Bull Creek watershed. Since the Jollyville Plateau springs are fed by upland recharge, the similarity of Backdoor Springs may indicate that it also receives recharge from nearby rural uplands and is currently minimally affected by urban activities. New development in the nearby upland area may change the chemistry of this spring in the future.

Both nitrate and TKN concentrations in Backdoor Springs (Table 2.7) are similar to Barton Springs and generally higher than the other three springs (Eliza, Old Mill, and Cold). The significance of this fact is unclear with the current amount of data available. The cause of the relatively high nitrate and TKN may be related to past effluent disposal from the Travis Country Package Treatment Plant. Treated effluent was sprayed over the uplands near the spring until the plant and irrigation system were taken off line in 1994. Upland recharge may contain greater concentrations of nutrients leached from soils (Barrett and Charbeneau, 1996).

Metals detected on Backdoor Spring include those commonly found in other springs, barium and iron. However, low concentrations of nickel, silver, and lead were detected separately in three different samples during 1995. Nickel is frequently detected in spring samples, although in greater concentrations in springs in urbanized settings. Hem (1989) notes that the concentrations of nickel in river water probably reflected its natural abundance and its extensive cultural use.

2.5.5 Comparisons Between Edwards Springs

While a large amount of water chemistry data is available for Barton Springs, much less data are available for the other springs discharging from the BSEA.

DataSondes have been placed in each Old Mill and Cold Springs while a second DataSonde has been deployed in Barton Springs to compare basic water chemistry and responses to specific rain events. Unfortunately, no rains occurred during these dual deployments. However, this effort has provided data for comparisons of basic water properties among the three springs. In the following figures, the data for Old Mill and Barton were collected over the same time period in early 1996, whereas the data for Cold Spring were collected in the days immediately following and overlaid for comparison. Figures 2.34, 2.35 and 2.36 compare temperature, pH, and specific conductance and illustrate noteworthy differences among these otherwise similar springs.

Temperature indicates that Cold Springs, as its name implies, is nearly a degree cooler that Barton. Cold Springs' specific conductance is much lower than either Barton or Old Mill. The pH in Cold Springs is between Barton and Old Mill. Old Mill has a slightly lower temperature than Barton, possibly because of exposure of the garden pool to cool winter weather. Higher specific conductance in Cold Springs may result from contributions of harder waters from the area of the bad water line or other sources.

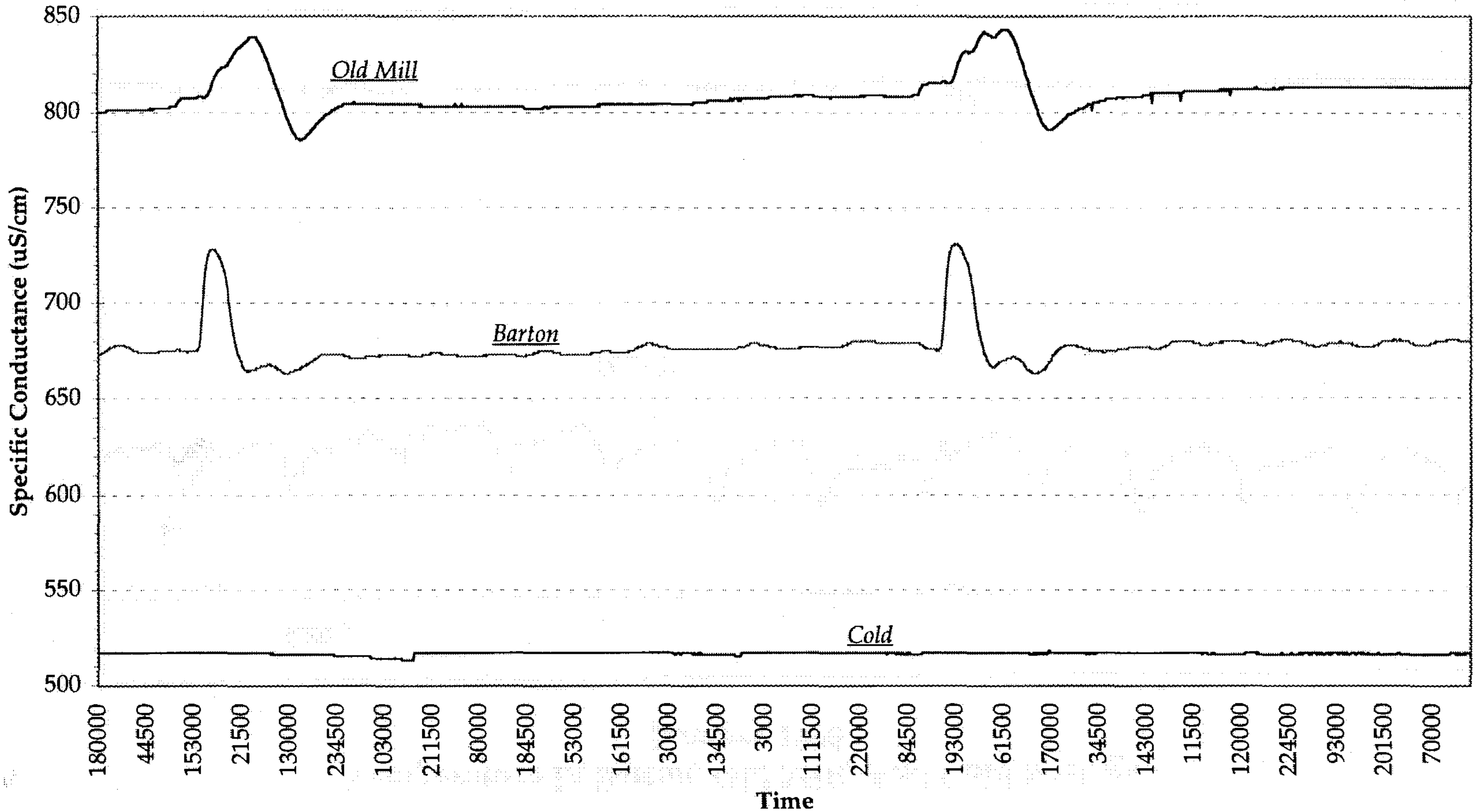
Differences in basic water chemistry may be due to the dominant source of water for each spring and residence time in the aquifer. The source of water for Cold Springs is generally thought to be the Rollingwood area, Eanes Creek, and probably the upper part of Barton Creek (Senger and Kreitler, 1984).

Cold Springs' specific conductance is much closer to that of surface water and may be indicating a relatively direct surface water recharge source. A partial record from deployment in Cold Springs in April 1995 shows a steady decrease in specific conductance over a 10 day period from 530 to 470 us/cm (Barton Springs remained constant at about 540 us/cm). USGS records (USGS, 1995) indicate rain increased flow in Barton Creek, as measured at Lost Creek Blvd., just before the DataSonde was put in the spring. Specific conductance measured in Pool 9, in Barton Creek immediately above the Recharge Zone, in May was approximately 480 us/cm, a drop from approximately 590 us/cm in February. The change in Cold Springs specific conductance during April 1995 may be due to recharge of low ionic strength water in Barton Creek following rains in early April. Cooler temperatures in Cold Springs in the winter (Figure 2.35) may be due to recharge of cold winter surface water and a fairly quick travel time to the spring.

Another potential source of water to Cold Springs includes Town Lake and Lake Austin. Monitoring in Town Lake at Red Bud Isle upstream of Cold Spring shows lake water with a specific conductance of 510 to 530 us/cm in early 1996, close to that in the spring. Town Lake appears to be an unlikely source of recharge to the springs since the water surface is lower than the spring discharge point. Water recharging from Lake Austin upstream of Tom Miller dam is possible. However, the flow path of this water would be against the regional flow as it is

Figure 2.34

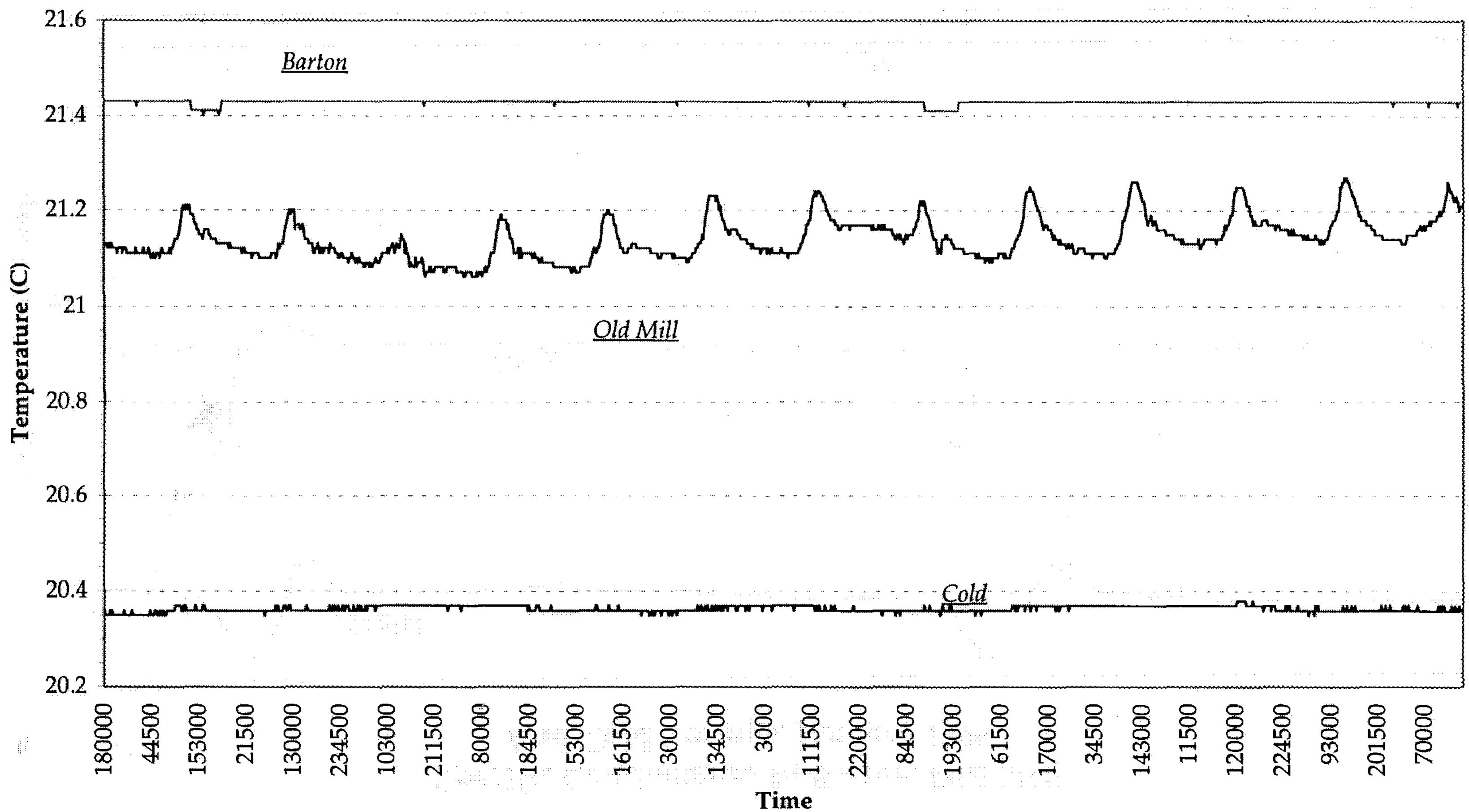
Specific Conductance In Barton, Old Mill And Cold Springs, January 1996



Source: COA/DUD Database

Figure 2.35

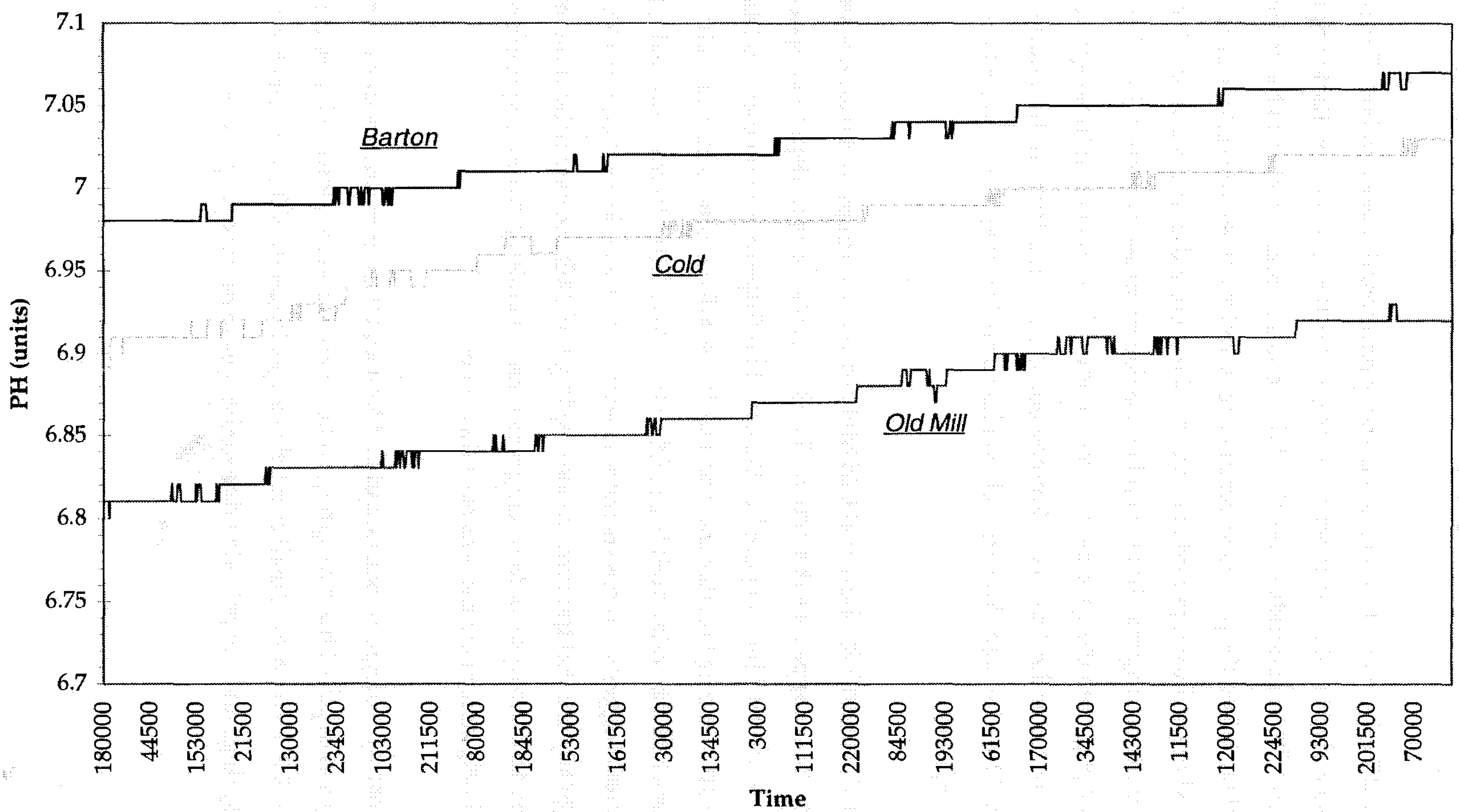
Temperature In Barton, Old Mill, And Cold Springs, January 1996



Source: COA/DUD Database

Figure 2.36

Comparison Of PH From Barton, Old Mill, And Cold Springs, January 1996



Source: COA/DUD Database

currently known. Therefore, based on hydrologic considerations, these lakes are unlikely sources of recharge to Cold Springs.

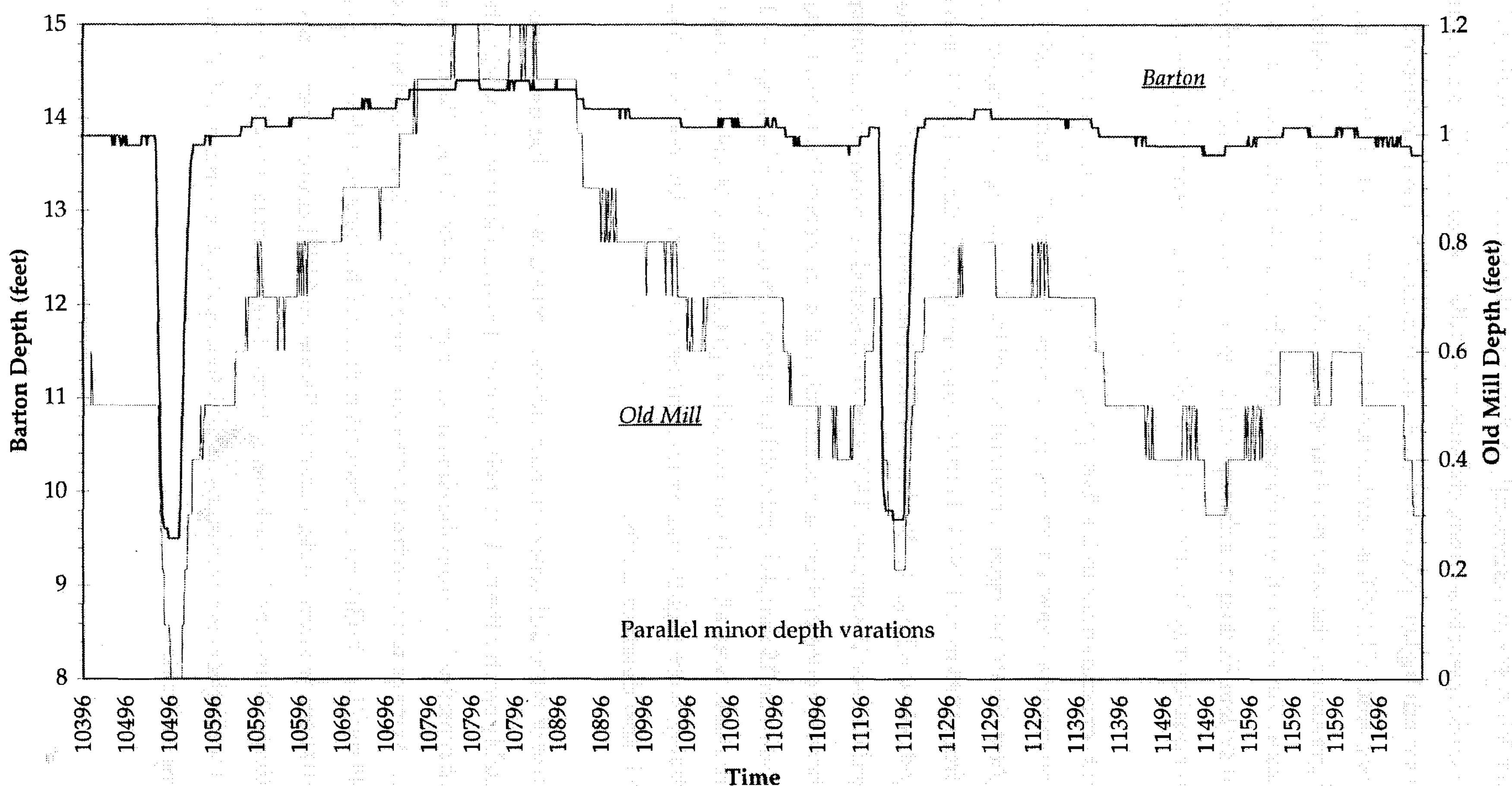
Figure 2.34 shows sharp increases in the specific conductance in both Barton and Old Mill Springs. These spikes correlate with drops in water levels when Barton Springs pool is cleaned. The magnitude or height of the spikes appears related to the frequency of pool lowering. When the pool is lowered once or twice a week the spike can be 50 to 90 us/cm high, whereas during periods of daily pool lowering the spikes are only 5 to 10 us/cm high. This evidence suggests that the spikes are due to pulses of more mineralized water discharging from the springs. One possible explanation is that these spikes result from matrix water in the limestone draining out as the water level in the aquifer near the spring drops. More frequent lowering allows less time for water-rock interactions in the small matrix spaces.

Figures 2.34 and 2.37 show that Old Mill responds to drops in the local water table closely with Barton. There appears to be only a 15 to 30 minute delay in depth and specific conductance response in Old Mill compared to Barton. The shape of the spike in Old Mill is slightly different from Barton, being broader and shorter. If the spike is due to matrix water, the shorter spike suggests that the water draining to Old Mill is less different from normal Old Mill water and the broadness suggests it recovers more slowly as the water levels begin to rise. Implications geologically are that the flow system feeding Old Mill appears to be more matrix-dominated than Barton. Analysis of the changes in water chemistry during a specific conductance spike would help determine the source of this water.

The close hydrologic association of Old Mill and Barton Springs is demonstrated by comparing changes in depth of the two springs when water levels are lowered in Barton Springs pool (Figure 2.37). Apparent small parallel changes in depth of 0.1 to 0.2 inches are present in all three springs and are probably due to changes in barometric pressure.

Figure 2.37

Depth In Barton and Old Mill Springs, January 1996



Source: COA/DUD Database

The five BSEA springs chemically plot very similar to each other, with Old Mill trending toward enrichment in sodium, chloride, and sulfate (Figure 2.17). As discussed previously, Old Mill has much higher specific conductance, presumably due to influence by water from the bad water line area. Old Mill is located east of Barton Springs, closer to the bad water line and would presumably be the first of the springs affected by more saline water invading the fresh water zone. An alternative explanation could be that Old Mill may have a slightly different conduit system feeding it, although still integrated into the overall Barton Springs system, and its water quality may be affected by development in the Barton Hills neighborhood.

Nutrient concentrations in the five springs are all relatively low but show distinct differences based on samples collected over a similar period (Table 2.7). Barton and Backdoor Springs have the highest nitrate-nitrogen concentrations of the five springs, averaging approximately 1.5 mg/L from 1993 to mid-1996. During this same period Eliza, Old Mill, and Cold Springs all averaged below 1.2 mg/L. Barton had more frequent detection for TKN than other springs and averaged 0.62 for 19 samples. TKN was not detected consistently in other springs. Ortho-phosphorous concentrations are commonly below detection limits but Barton averaged 0.02 mg/L based on 15 samples and Cold averaged 0.08 mg/L for 14 samples. Total phosphorous concentrations were all fairly similar although Cold and Old Mill, 0.07 and 0.06 mg/L respectively, were slightly higher than the other springs. Ammonia concentrations were all near or below detection limits.

The cause of these differences in nutrient concentrations is not known, since all the springs presumably receive the bulk of their recharge from creek flow. A possibility is different nutrient contributions from the closest recharging creeks - Eanes, Barton, and Williamson Creeks. Average nitrate-nitrogen concentrations for baseflow in Barton Creek are 0.16 mg/L and 0.46 mg/L in Williamson Creek (Barrett and Charbeneau, 1996). Average nitrate-nitrogen concentrations in storm water runoff in Barton and Williamson Creeks are 0.23 and 0.35 mg/L respectively (Barrett and Charbeneau, 1996). Higher nitrate in Williamson Creek may partly account for higher concentrations in Backdoor Springs, assuming it does receive recharge from Williamson Creek.

Nitrate concentrations in Cold Springs are low (Table 2.7) especially considering that most of the area upgradient of it in Rollingwood is developed and much of the suspected recharge area is serviced by on-site wastewater systems. Two samples have been collected from the spring and analyzed for nitrogen isotopes to try to determine the source of nitrogen in the springs. One sample collected 9/22/94 had a del 15N of 7.7 and the second collected 4/12/95 had a del 15N of 4.1. The first sample is closer to the range that would suggest anthropogenic input (>10), but the latter is clearly in the range of background soil nitrogen. Flow conditions in Barton Creek were very different during the two collections. Barton flow at Lost Creek Blvd. was 0.36 cfs on 9/22/94 and 57 cfs on 4/12/95 (USGS, 1994, 1995). The lower isotopic value on 4/12/95 may be the result of dilution of an anthropogenic nitrogen source from waters recharging from Barton Creek or other recharge sources during a wet period.

Nutrient concentrations in surface water are generally lower than in ground water. In the case of Barton Springs, a significant amount of the nitrate-nitrogen detected in the springs must originate from a source other than surface recharge. Santos, Loomis and Associates (1995) estimated known nitrogen input to the system and determined that most of the nitrogen source is unknown. As the nitrogen is not detected in surface water, it must be entering the aquifer from upland recharge either from rainfall and soil nitrogen or from anthropogenic sources. A greater proportion of nitrogen from rainfall was in fact proposed in a later nitrogen balance provided in Barrett and Charbeneau (1996).

2.5.6 Discussion

The BSEA is Karst terrain as indicated by geomorphic features such as caves, sinkholes, and losing creeks, and a Karst aquifer with flow through solution-enlarged faults, fractures, bedding planes and other cavities (Quinlan and others, 1992). The aquifer can be classified based on recharge, storage, and flow and a measure of sensitivity based on the aquifer's response to variations in these parameters (Quinlan and others, 1992). Recharge to the BSEA is predominately point recharge where 85 percent of the water enters the aquifer mainly through specific features in the channels of six main creeks crossing the aquifer Recharge Zone (Andrews and others, 1984). Storage in the aquifer is relatively high based on a thick unsaturated zone, and an estimated saturated thickness of 430 feet in the confined zone (Slade and others, 1985). Storage is less in the Recharge Zone where water levels can fluctuate up to 100 feet (Hauwert and Vickers, 1994; Slade and others, 1985) and erosion has thinned the aquifer. Flow in the BSEA appears dominated by conduits based on the abundance of caves in the Edwards, rapid rises in water levels following rain, field observations of spring discharge points, spring responses to rain events, and rapid drops in water levels.

Using the aquifer classification system of Quinlan and others (1992) and the aquifer attributes outlined above, the vulnerability of the BSEA can be classified as a very sensitive Karst aquifer with rapid recharge, fast ground water migration, and high storage. These aquifers are vulnerable to ground water contamination by virtue of rapid recharge and rapid migration characteristics. These characteristics are reflected in the rapid increases in flow and changes in chemical quality in Barton Springs following rain events.

Further distinction of the vulnerability of the aquifer can be determined by analyzing geochemical variations in spring discharges. Shuster and White (1971) defined aquifers using a coefficient of variation (CV) of conductivity. The CV is calculated by multiplying the standard deviation by 100 and dividing by the mean. Diffuse flow aquifers have a CV of less than five percent while conduit-flow aquifers have a CV over 10 percent. Quinlan and others (1992) defined these values as boundaries for hypersensitive aquifers (CV greater than 10 percent), very sensitive aquifers (CV between five and 10 percent), and moderately sensitive aquifers (CV less than five percent). Using specific conductance data measured every six hours gathered by multiprobe deployment between April 1994 and May 1996, the CV for Barton Springs is 9.7 percent. This classification suggests that the BSEA is very vulnerable to contamination. More specifically, Barton Springs is probably more sensitive to short term pulses and chronic contamination in Barton Creek, as suggested by spring response to rainfall and proximity to the springs, and by long term chronic contamination from other recharge creeks. Recently, large variations in spring chemistry have been found to be more related to rapid recharge through point recharge features rather than being due to conduit or rapid flow through the aquifer (ASTM, 1995, Worthington and others, 1992). In either case, contaminants may enter the aquifer rapidly with minimal attenuation.

In-situ data logging can be used to estimate aquifer properties near the springs. DataSonde data show that decreases in the pool water level are closely followed by a spike in specific conductance, a trough in dissolved oxygen, and occasionally a change in temperature. Analysis of specific conductance data indicates that when the pool water level is dropped once or twice a week, the increase in specific conductance is approximately 50-90 us/cm. More frequent drops in water level are followed by shorter spikes, on the order of 5 to 10 us/cm. This suggests that the spikes are due to more mineralized water discharging from the aquifer. The timing of the spikes is variable, a long lag between pool lowering and the spike under low flow conditions and a short lag during high flow conditions. The variation in height of the spike related to frequency of pool lowering indicates that the mineralized water may represent water draining from the rock pores and small voids where circulation is slow and rock-water interactions have longer to occur. The lag time represents conduit water that empties prior to draining the tighter rock matrix. Chemical analyses of water samples collected during the conductivity spike could verify the source of the high conductance water.

Recent water samples collected during a specific conductance spike indicates a sharp increase in sodium and chloride concentrations (Mahler, 1997). These constituents would not likely originate from limestone dissolution reactions and indicate a slug of water from the bad water zone entering the conduit system following lowering of the local water table during pool maintenance.

The total area affected by these water level drops is largely unknown. However, Senger and Kreitler (1984) measured drops in water levels in wells as much as 2.7 miles southwest of the springs (along Ben White Blvd.) that correlated with the drops in pool water. Water levels in these wells did not fully recover to levels present prior to draining the pool. This indicates that water is removed from storage in the aquifer during pool draining and is not replaced until creeks begin flowing over the Recharge Zone.

A graduate student from the University of Texas has been collecting sediment from numerous locations in the BSEA to determine if there are physical or chemical differences in sediment from the springs and other locations. Analysis indicates that some occurrences of sedimentation in wells is due to naturally occurring sediment or sediment derived from within the aquifer and not washed in from surface sources (Mahler, 1997). This research also documented surface-derived sediments discharging from the springs. Microscopic examination also revealed small bits of fiber and glass in the suspended sediment indicating a direct link to an anthropogenic source.

One of the main issues surrounding Barton Springs is whether the springs have been affected or degraded by urbanization. Time trend analysis of nitrogen data from the springs since the early 1980s does not show evidence of degradation (See Section 2.5.1.2). However, Barton Springs does show occurrences of tetrachloroethylene, heavy metals, and sediment that appear to originate from anthropogenic sources. Samples from other springs have detected total petroleum hydrocarbons, heavy metals, and pesticides. Localized occurrences of urban impacts have been found in water wells in the aquifer. These data indicate that the effects of urbanization are beginning to be identified in the aquifer. Because of rapid flow and limited filtering in the aquifer, greater impacts to the springs are likely as urbanization increases within the Recharge and Contributing Zones of the springs. Regular sampling of Barton Springs over a longer period may identify trends in water chemistry that are not evident at this time.

2.6 EDWARDS AQUIFER GROUND WATER CHEMISTRY

Chemistry of Edwards water has been the subject of numerous publications and university theses, including Abbott (1973), Browning (1977), Senger and Kreitler (1984), Andrews et. al. (1984), Baker et. al. (1986), Slade et. al. (1986), St. Clair (1979), Parten (1991), Hauwert and Vickers (1994), Johns (1994b), and Oetting et. al. (1996). Numerous additional publications are available for the San Antonio segment of the aquifer.

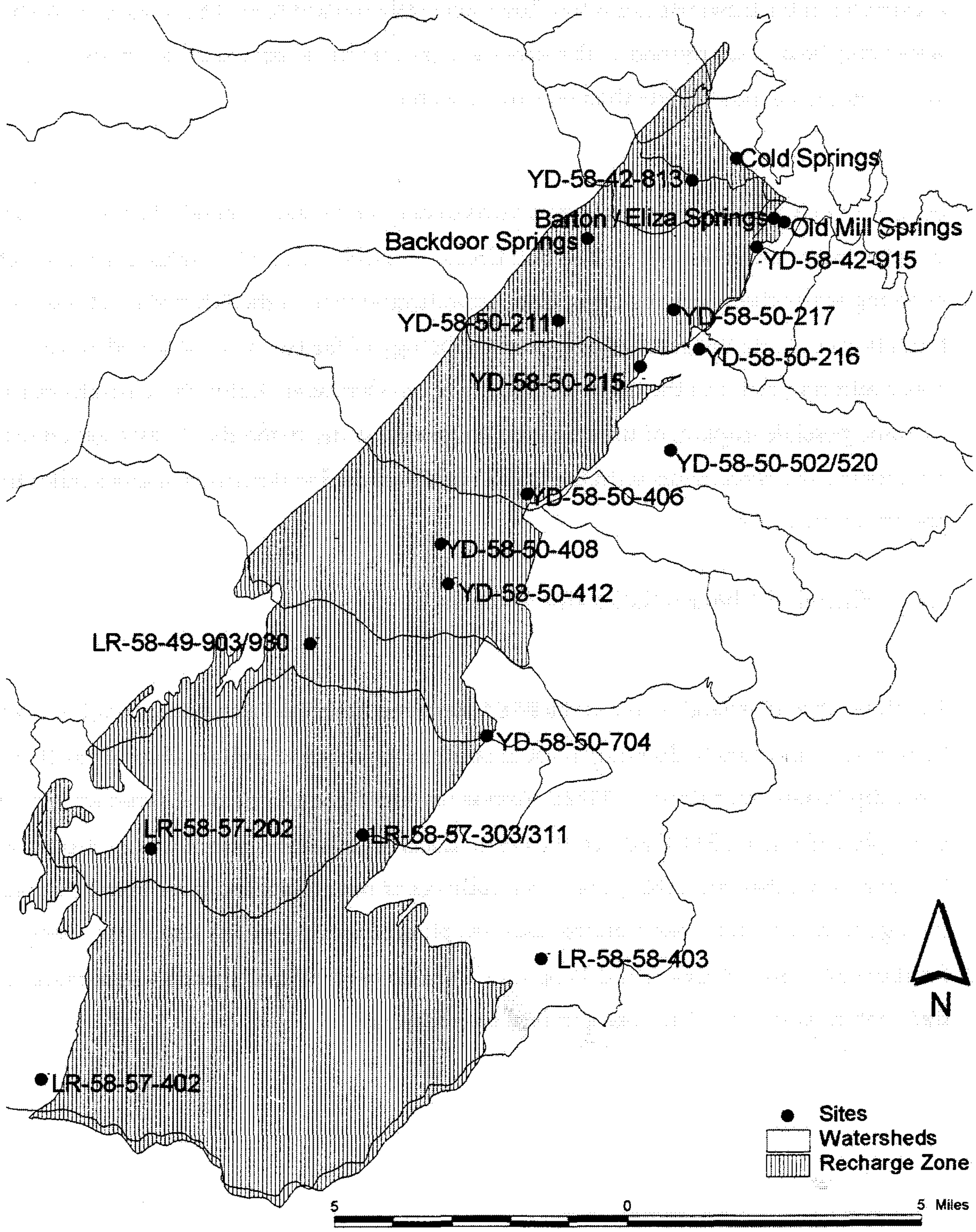
The City of Austin has been gathering data in the BSEA since 1986 through cooperative agreements with the USGS. Samples are regularly collected from numerous wells and Barton Springs (Figure 2.38), with results published annually in USGS Water Resources Data Reports. Since inception of the program, samples have been collected under a variety of aquifer conditions, low and high water levels, base flow and following storms. The goal of this effort is two-fold: to determine water chemistry characteristics of the aquifer and to determine effects of urbanization on the quality of ground water. Much progress has been made toward the first goal. Valuable data have been gathered to understand general water chemistry in the Edwards and provide a baseline for future comparisons for water chemistry in the aquifer. The second goal has been more difficult to achieve because of the complex nature of Karst aquifers (point recharge features, large flow conduits allowing rapid migration of water from great distances, and difficulty in determining local flow paths), the convergent nature of ground water movement in the Edwards (all water flows generally toward Barton Springs, so contaminated water may be quickly diluted with cleaner water), and the effects of urbanization on ground water tend to be more subtle than on surface waters.

For cases such as this, using analogous areas to help understand chemical characteristics of possible impacts can be useful. The Bull Creek watershed is an ideal setting to study differences in spring water chemistry resulting from urbanization in both the Edwards and Glen Rose formations because the geology and geomorphology of the basin are nearly identical. The major differing factor in the basin is intensity of development. Using these results as a model to examine possible impacts of urbanization on ground water in the BSEA, data gathered through the cooperative agreements with the USGS were analyzed to determine if any similar trends are present in the BSEA.

2.6.1 Chemical Characteristics and Analysis

The chemistry of ground water in the BSEA has been described as calcium bicarbonate that becomes sodium sulfate downdip (east or southeastward) and sodium chloride further downdip (Senger and Kreitler, 1984). Trends toward these geochemical facies are evident in Piper plots (Senger, 1984; Slade et. al., 1986). Local high sulfate concentrations are present in the Recharge Zone (Senger, 1983). These typically occur near faults and have been attributed to leakage from the Glen Rose Aquifer based on plots of sodium versus strontium. Senger and Kreitler (1984) and Hauwert and Vickers (1994) also used plots of sulfate versus chloride to differentiate between Glen Rose and Edwards waters.

Figure 2.38
USGS Springs and USGS Wells in the Barton Springs Edwards Aquifer



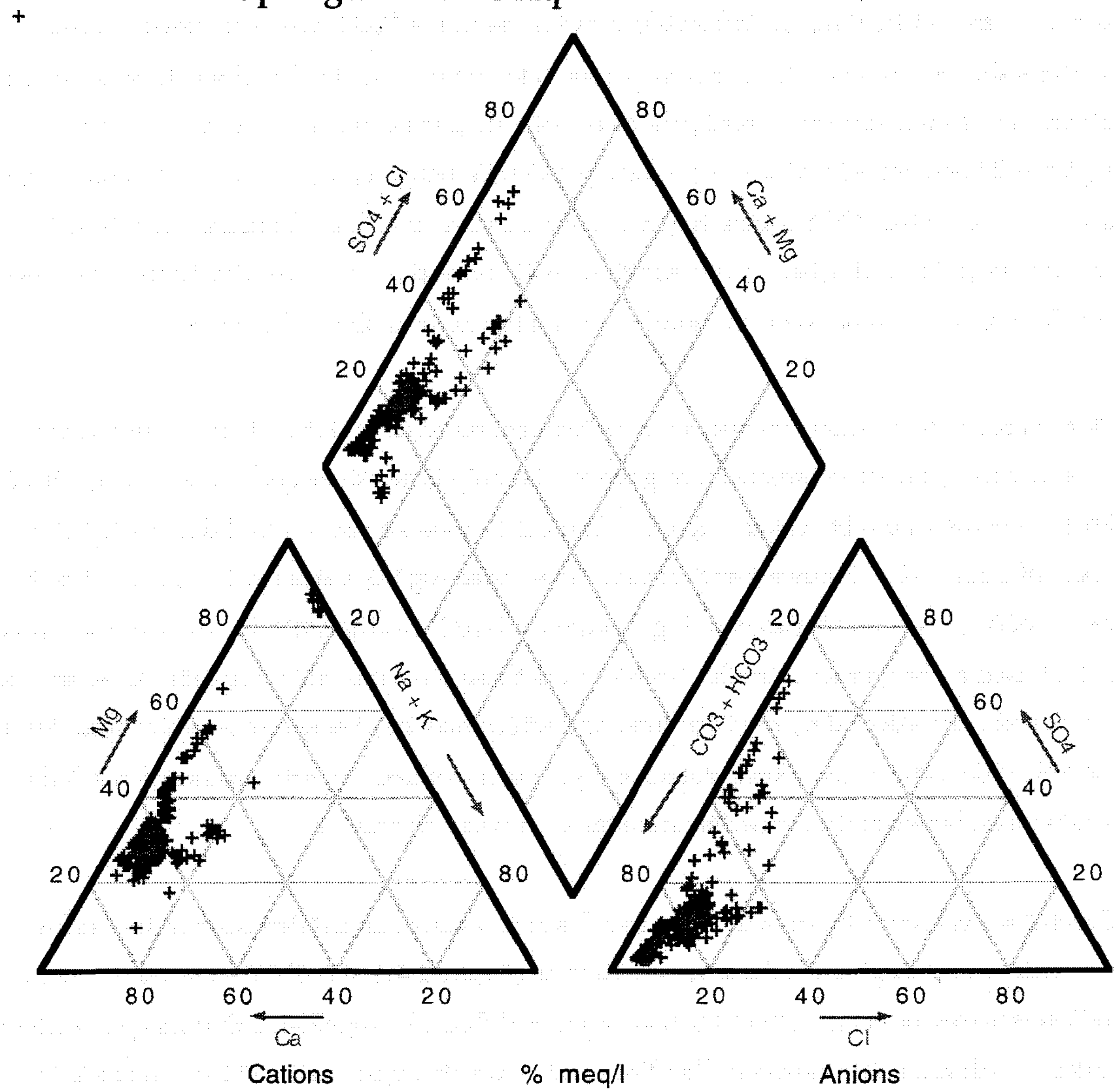
Piper plots of USGS data from BSEA wells (Figure 2.39) indicate a range in ion chemistry similar to that seen in Bull Creek ground water data, suggesting that urban impacts may be present similar to those identified in Edwards ground water in the Bull Creek watershed. Further analysis shows certain wells consistently plot in the higher sulfate plus chloride area, whereas others vary somewhat and a third group consistently plots in the low sulfate plus chloride region (<20 percent SO4+Cl). A significant problem in using ions, particularly sodium, sulfate, and chloride, in the BSEA is that they are also indicative of leakage from the Glen Rose Aquifer and the deep Edwards (Senger and Kreitler, 1984). Strontium, also used by Senger and Kreitler (1984) to distinguish between the aquifers, is not tested for in the USGS wells.

Plots were made of sulfate versus chloride (Senger and Kreitler, 1984; Hauwert and Vickers, 1994) to attempt to differentiate among wells with only Edwards water, those mixing with Glen Rose water, and possible urban impacts. Figure 2.40 shows a pronounced difference between many of these wells. Hauwert and Vickers (1994) used log SO_4 values of 1.5 to 2 and log SO_4/Cl values of 0 to 1 as boundaries defining a zone of mixed Edwards and Glen Rose water, similar to that used by Senger and Kreitler (1984). From these plots it is still impossible to determine which wells are affected by the Glen Rose and which may be affected by urbanization. Another variable indicative of Glen Rose waters and yet not introduced by urbanization is needed to differentiate between these possible influences on water chemistry.

Ground water chemistry data indicate that fluoride is also high in Glen Rose water yet low in Edwards water. A plot of sulfate verses fluoride (Figure 2.41) of Bull Creek ground water data indicates no relationship between urbanization and fluoride, suggesting that this parameter is suitable to differentiate between Glen Rose and Edwards waters in the BSEA. Figure 2.42 shows a distinct spread in fluoride/sulfate for the BSEA wells. Well YD-58-50-216 is a good guide for interpreting fluoride concentrations resulting from inflow from adjacent aquifers as concentrations of fluoride, sulfate, and chloride in this well display very good correlation with discharge from Barton Springs. Based on this well, wells with values greater than 1.9 log SO4 and -0.3 log F clearly have significant contributions from adjacent aquifers. Some wells, with variable water levels in the aquifer, may have small volumes of Glen Rose water mixing with the Edwards. These wells plot greater than 1.4 Log SO4 and -0.4 Log F. Using this method, four wells LR-58-57-402, LR-58-49-903/930, YD-58-50-408, YD-58-50-216, and possibly LR-58-58-403

Figure 2.39

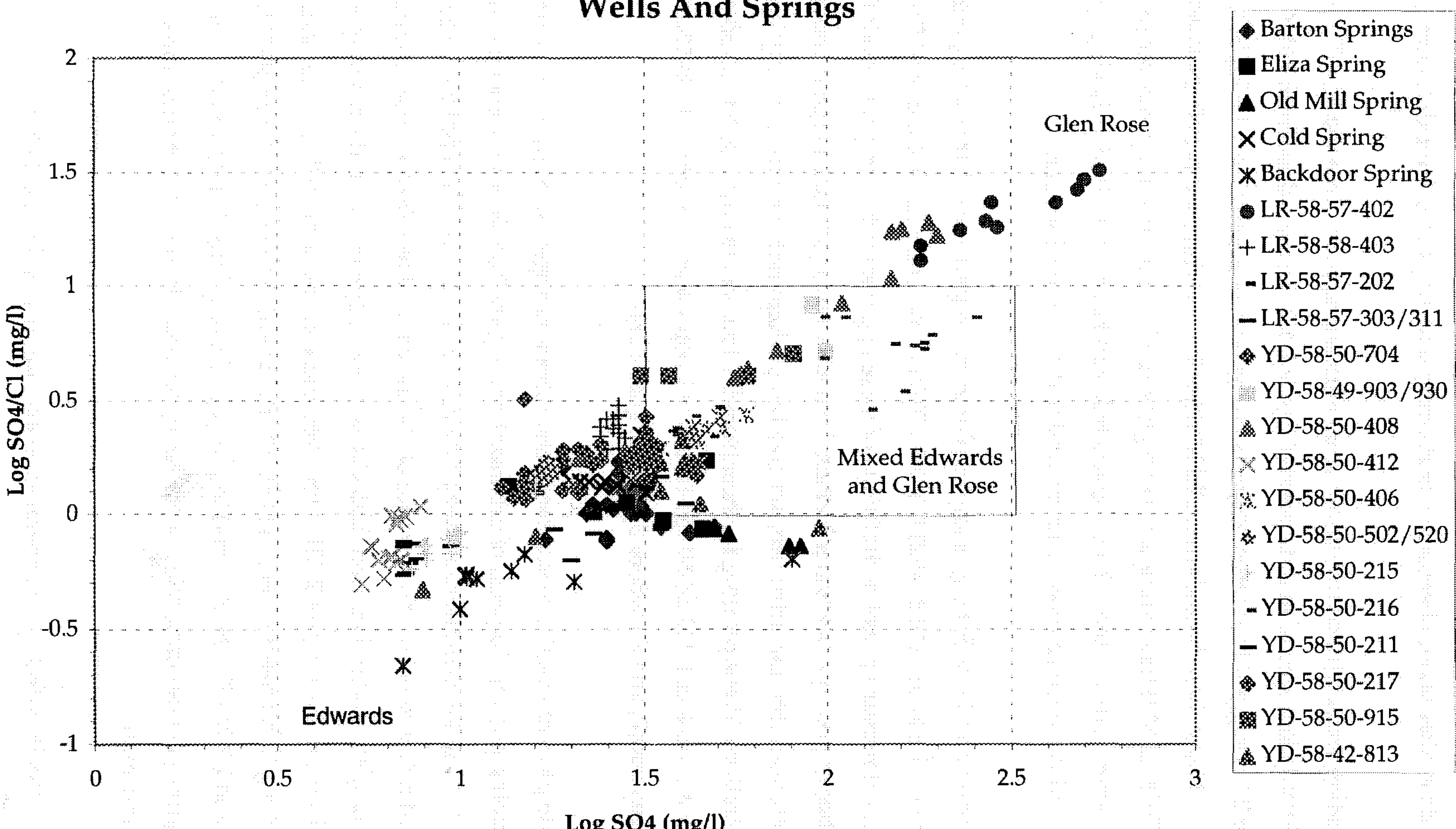
Barton Springs/Edwards Aquifer USGS Well Ion Data



Source: USGS Water Resources Data 1986-1993

Figure 2.40

Sulfate And Chloride Relationship in BSEA Wells And Springs



Source: COA/DUD Database 1995-1996
USGS Water Resources Data 1986-1993

(Figure 2.38) are interpreted as having enough leakage from the adjacent Glen Rose and deep Edwards to alter water chemistry significantly with respect to fluoride, sulfate, and chloride.

Eliminating wells with contributions from adjacent aquifers from the SO4/Cl plots generates considerably less spread in data points (Figure 2.43). Using values from Bull Creek plots (Figure 2.12) suggest that urban impacts plot generally greater than 1.6 log SO4 and -0.4 log SO4/Cl. Using these boundaries, Old Mill Spring and three wells (YD-58-42-915, YD-58-50-406, and YD-58-42-813) have anomalously high SO4/Cl values that may indicate impact from urbanization. Sites in the urban impacts field can be characterized as having ground water with higher sulfate concentrations than ground water in a rural setting.

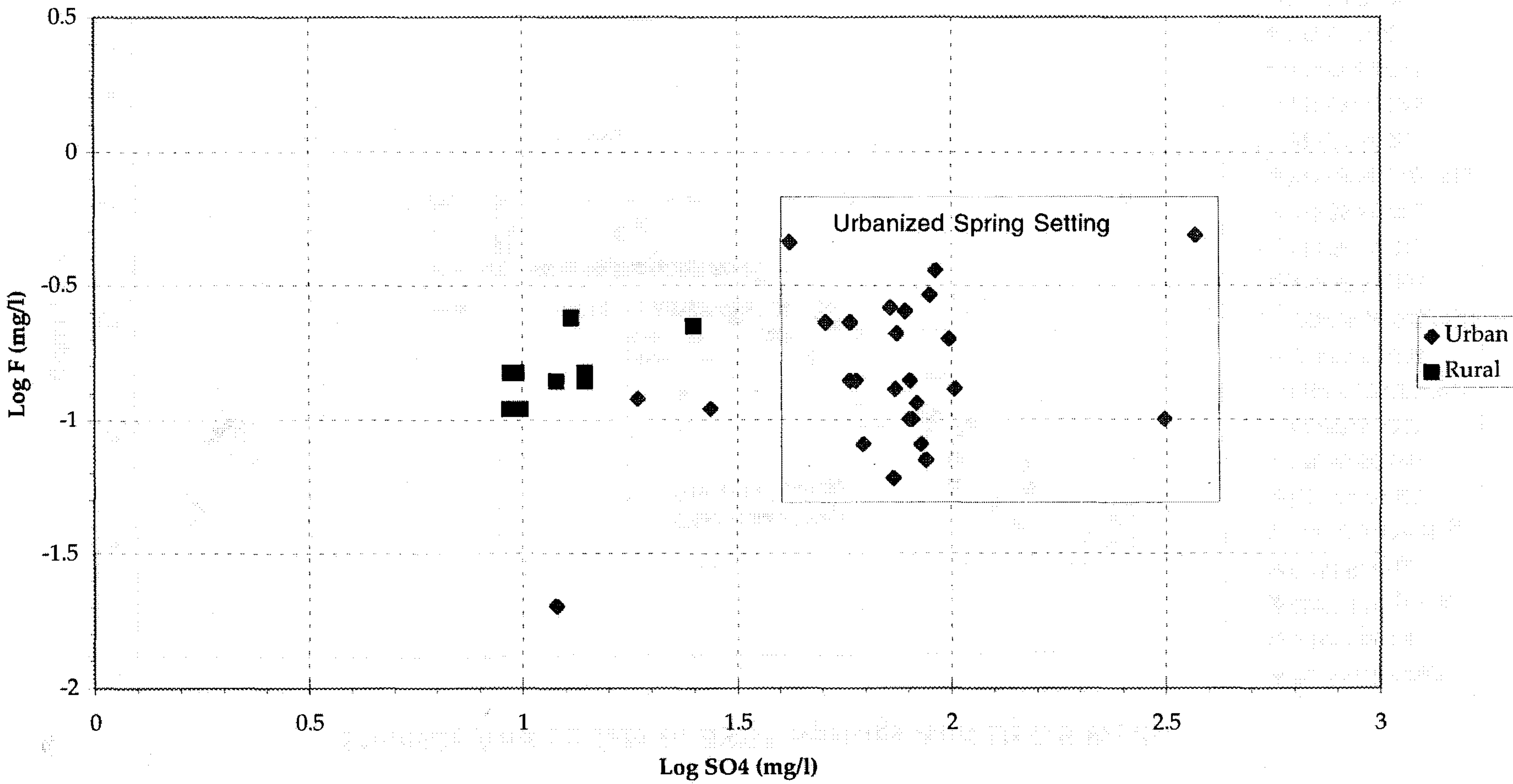
Two Barton and Eliza Springs samples plot in the impact area. Other sites plotting near the impact area include YD-58-50-217, YD-58-50-211, and some Eliza, Cold, and Barton Springs samples. It remains possible that some of these apparent urban impacts result from small quantities of poor quality water leaking from adjacent aquifers, enough to move the SO4/Cl concentrations into the urban impact area but perhaps not enough to greatly increase fluoride concentrations. Wells plotting furthest from the impact area include YD-50-50-412 (until recently a rural area), YD-58-50-215 (south of Loop 1 and U. S. 290), LR-58-57-303/311 (primarily rural), and Backdoor Spring (Figure 2.38).

Bivariate plots of specific conductance and nitrate-nitrogen also appear to be useful for determining possible impacts of urbanization. Figure 2.44 shows springs and wells without influence from the Glen Rose or deep Edwards in the BSEA. Data points are generally tightly clustered below specific conductance of 700 us/cm and less than 1.5 mg/L nitrate-nitrogen. The analogous model data from Bull Creek do not appear to be reflected in specific conductance values in the BSEA (Figure 2.13). However, there are several wells that consistently plot greater than 1.5 mg/L nitrate-nitrogen: YD-58-50-406, YD-58-50-215, and YD-58-50-211. Wells YD-58-50-412 and LR-58-57-303/311 tend to plot just above 1.5 mg/L nitrate-nitrogen. Based on Bull Creek ground water data, these wells have elevated nitrate concentrations that may be caused by urbanization.

Sites potentially affected by urbanization are summarized in Table 2.9.

Figure 2.41

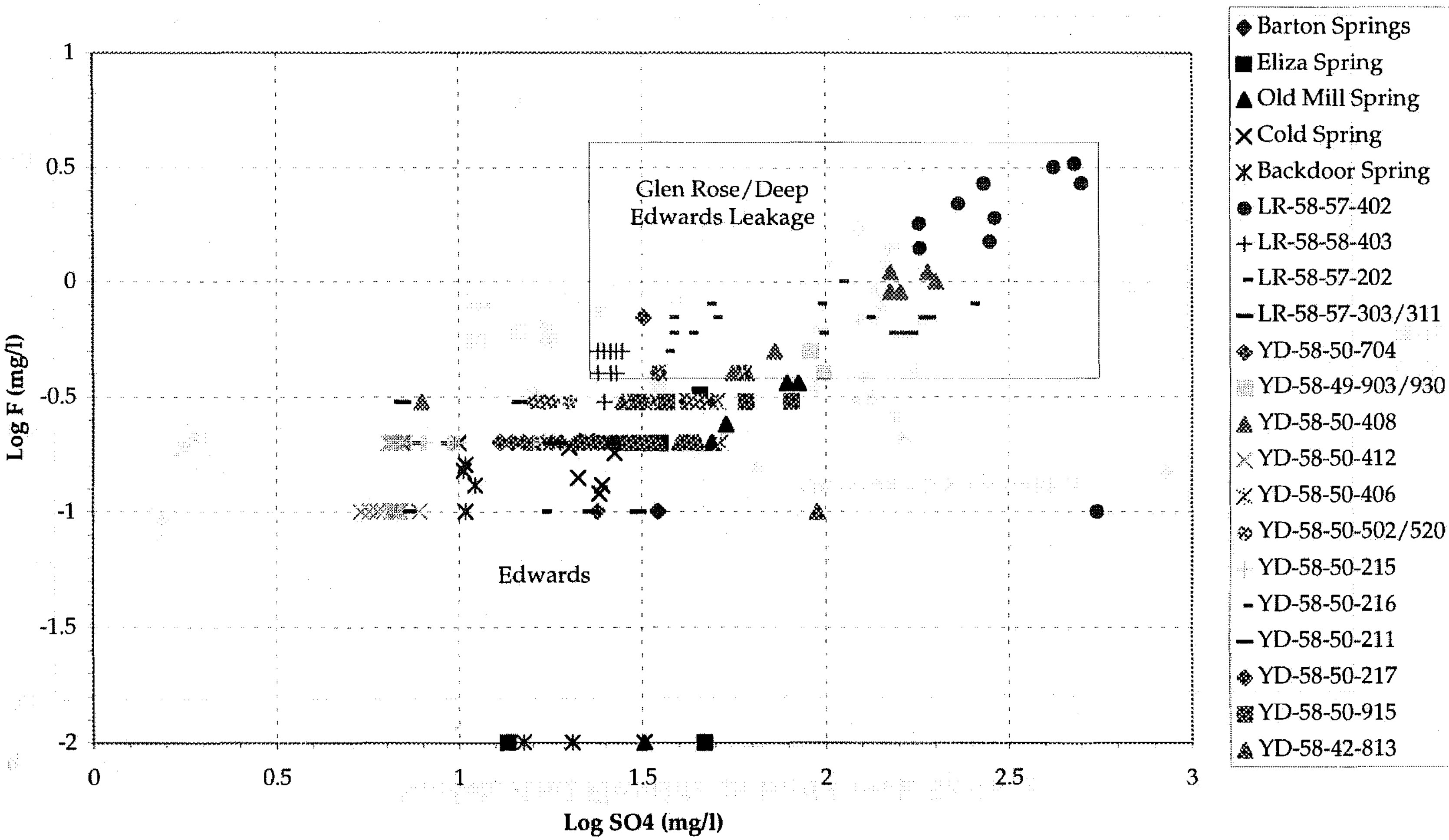
Sulfate And Fluoride In Bull Creek Springs



Source: COA/DUD Database 1993-1996

Figure 2.42

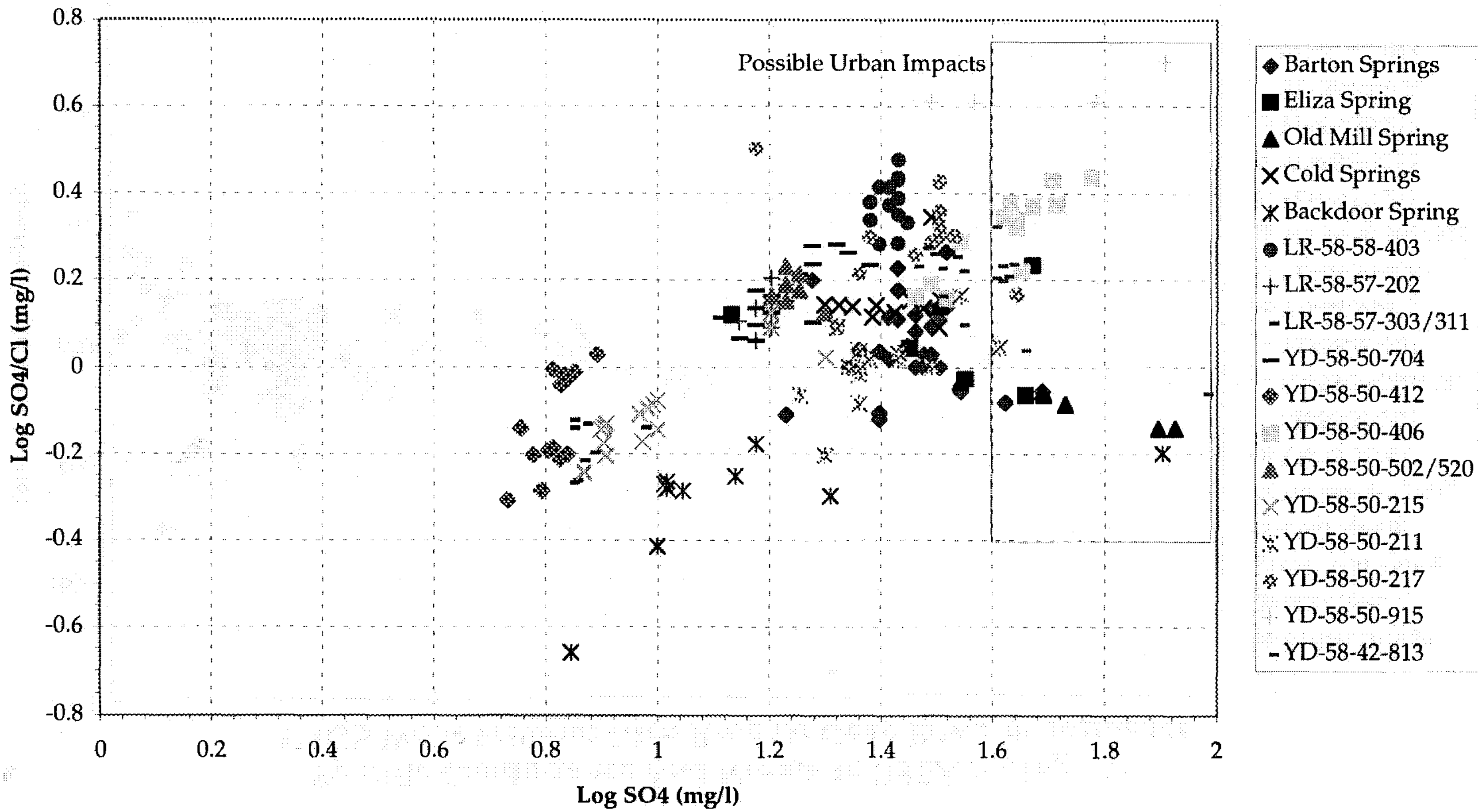
Fluoride And Sulfate In BSEA Springs And USGS Wells



Source: COA/DUD Database 1995-1996
USGS Water Resources Data 1986-1993

Figure 2.43

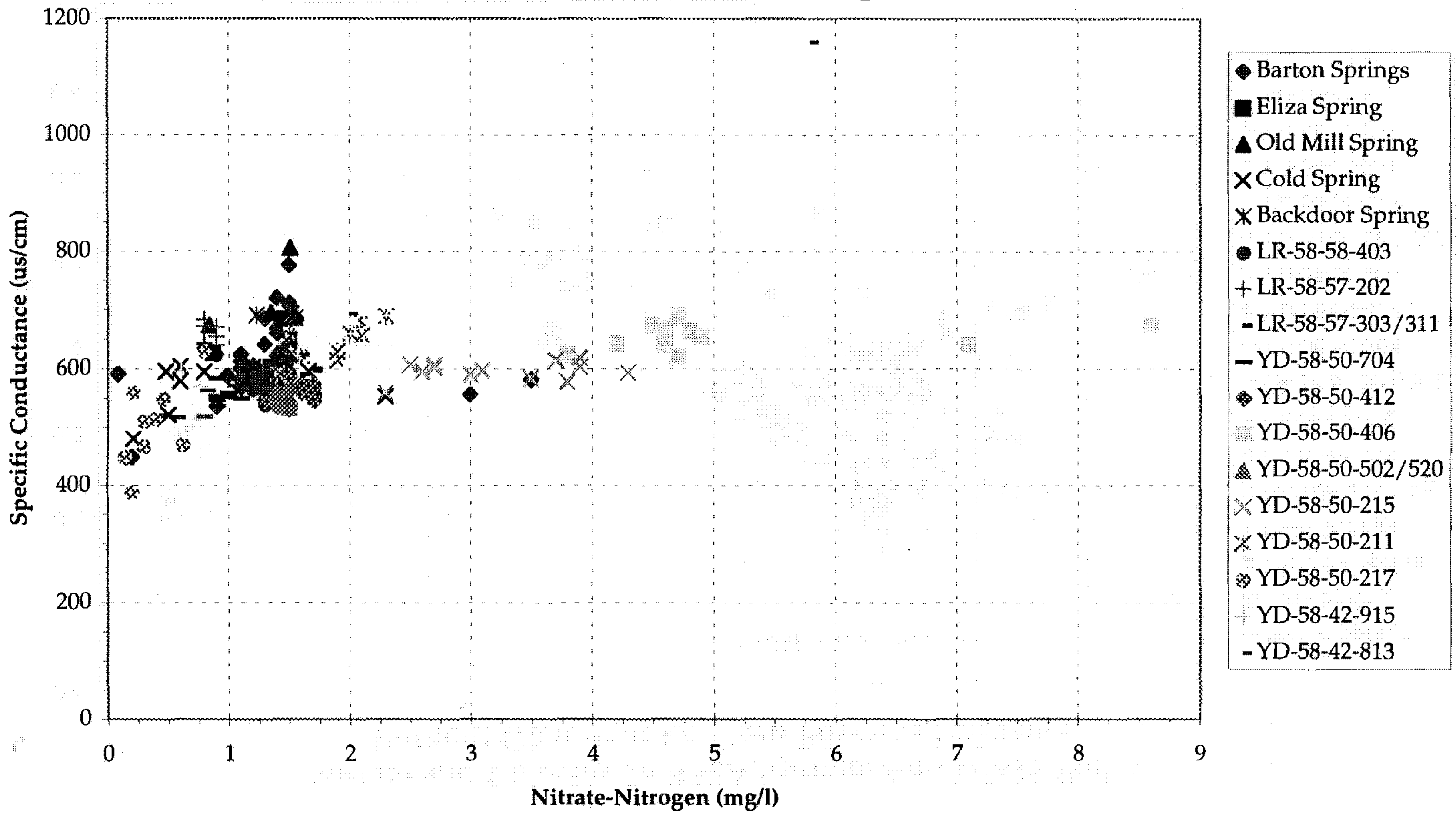
Sulfate and Chloride In BSEA Springs And USGS Wells Without Glen Rose Or Deep Edwards Influence



Source: COA/DUD Database 1995-1996
USGS Water Resources Data 1986-1993

Figure 2.44

Specific Conductance And Nitrate In BSEA Springs And USGS Wells Without Glen Rose Or Deep Edwards Influence



Source: COA/DUD Database 1995-1996
USGS Water Resources Date 1986-1993

Table 2.9 Sites in BSEA Potentially Affected By Urbanization

Site	SO4/Cl	NO3-N
Old Mill Spring	X	
YD-58-42-915	X	
YD-58-50-406	X	X
YD-58-42-813	X	
YD-58-50-215		X
YD-58-50-211		X
YD-58-50-412		X
LR-58-57-303/311		X

2.6.2 Discussion of Results

Wells and the springs exhibiting urban characteristics are mostly located in the northern end of the aquifer where urban development is greatest and the oldest (Figure 2.38). Point and nonpoint source pollution problems would be expected to be greatest in this area. These problems include older on-site wastewater disposal systems (septic tanks), older central wastewater collection lines, dense home sites with turf grass lawns (fertilizer application), accidental spills of chemicals, and possibly greater fallout of airborne contaminants which rainfall could carry to ground water.

Both sulfate/chloride and nitrate/specific conductance data indicate problems with well YD-58-50-406. Local animal operations (pigs and goats) could be the source if the well casing is bad. There are also several major surface Karst features within a half mile south of this site which could be directing poor quality surface runoff into the aquifer.

Well YD-58-42-813 is in an area serviced mainly by septic systems. This well was required to be abandoned and plugged several years ago because of bacteria contamination. Deteriorated well casing was allowing surface and near surface water to funnel down the well casing to the water table.

Well YD-58-42-915 is located in the Barton Hills area where infrastructure lines are old. Some large animals on site could represent a contamination problem although well construction appears good. There is only a small amount of data for this well compared to others so water chemistry variations related to water level changes could not be studied.

Nitrate data indicate anomalously high concentrations in well YD-58-50-215. This well appears to be downgradient of most of the community of Sunset Valley. Leaching of nitrates from septic systems or lawn fertilizers could increase nitrate in the local ground water.

Nitrate data also indicate possible urban impact in well YD-58-50-211, although sulfate/chloride data do not reflect any problems. This well is in an area where effluent from a package treatment plant was disposed of by irrigation over a relatively small upland area. This plant was recently decommissioned when the subdivision was connected to the COA central wastewater collection system.

Old Mill Spring may be impacted by urbanization based on sulfate/chloride data. Nitrate data do not indicate unusual concentrations. However, TPH has been detected (Hauwert and Vickers, 1994) which does show that some urban impacts are present at least on a temporary basis.

Barton Springs is, of course, at the lowest end of the hydrologic system and receives water from all the contributing watersheds, including the heavily urbanized areas closest to the springs. Two Barton Springs samples, plotting in the impact area, were collected during low flow conditions (less than 30 cfs) when dilution of urban pollution by cleaner rural water would be less. However, this would also be when influence from adjacent aquifers would be expected to be greatest.

Some of the wells with obvious mixing of Glen Rose and Edwards water have unusual characteristics. For example, well YD-58-50-216 sometimes displays geochemical characteristics of "typical" Edwards or mixed waters. Analysis indicates that during high water table conditions (i.e. high discharge from Barton Springs), this well has "typical" Edwards water and during low water table conditions has more Glen Rose or "bad water line" water. Senger and

Kreitler (1984) hypothesized that water invaded the fresh water zone from the "bad water line" when potentiometric surfaces were low. However, well TD-58-50-408 displays just the opposite trend, with the most sulfate rich samples collected during high water table conditions. The cause of this condition is unknown but may be related to fault structures.

2.7 CONCLUSIONS

Springs are a vital component of the Barton Creek ecosystem. Springs are focused discharge points for shallow ground water tables which store water following rains, maintain base flow in tributaries and creeks, and discharge cool waters slightly enriched in nutrients to stimulate biologic communities. Springs are literally the life blood of a surface water system. Areas of ground water discharge sustain pools within Barton Creek during periods of scant rainfall. Analysis of water chemistry in springs provides data to determine diffuse chemical inputs to the surface water system that are derived from natural sources or human activities and can help determine the effects of chronic or catastrophic activities in spring recharge areas.

Flow measurements in tributaries of Barton Creek and other watersheds indicate that moderately dense urban development can have severe effects on base flow characteristics. Rural watersheds and those with low-density housing displayed well-defined positive relationships between flow volume and drainage area. This pattern is attributable to two factors. Impervious cover in urban watersheds prevents rain water infiltration from feeding shallow ground water tables which then slowly discharge water into creeks as baseflow. Unusually high discharges in urban tributaries can result from infrastructure leaks or irrigation. Calculations show an urbanized tributary with effluent irrigation had a yield per acre nearly an order of magnitude greater than any rural or low-density urbanized watershed. This tributary also had perennial flow when other tributaries of similar and larger size were dry. These unusual flow characteristics were likely sustained by the effluent irrigation practices.

Significant differences in ground water chemistry have been identified between springs located in urban and rural areas in the Contributing Zone of the Barton Creek Watershed. Higher concentrations of total dissolved solids, total Kjeldahl nitrogen, calcium, potassium, nitrate, sodium, chloride, sulfate, alkalinity, and TOC are found in urban ground water. Although the differences between urban site and rural site parameter concentrations are statistically significant, indicating an impact of urbanization, ground water quality in urban areas remains good relative to drinking water standards. Elevated nitrate concentrations detected in the spring at Site 72/73 have also been detected in the pool downstream of the spring. This pool consistently has higher nitrate concentrations than any other pool site on Barton Creek. The probable sources of the nitrate are effluent holding ponds and effluent irrigation on a nearby golf course. This conclusion is supported by evidence of high nitrogen isotope ratios in the spring which approach wastewater signatures. This spring also maintained relatively high discharge during prolonged drought conditions which dried up many springs and most surface flow in Barton Creek. Discussions have begun with golf course personnel to examine this problem.

Five large springs discharge from the BSEA either into Barton Creek or they may receive recharge water from Barton Creek. Of the five springs, Barton, Old Mill, Eliza, Cold, and Backdoor, Barton and Backdoor have the highest nitrate-nitrogen concentrations, approximately 1.5 mg/L during the same period. Concentrations in the other springs are closer to 1.15 mg/L. Data from *in-situ* multiprobe measurements from Barton, Old Mill, and Cold Springs show slight but consistent differences in basic water chemistry. Specific conductance is highest in Old Mill and lowest in Cold Springs; temperature is highest in Barton and lowest in Cold Springs; and pH is highest in Barton and lowest in Old Mill Springs. These differences are probably related to recharge areas, land use, and flow paths to each spring. Cold Springs appears to receive significant recharge from Barton Creek based on water temperature, specific conductance, ion chemistry, and nitrogen isotope ratios.

Water chemistry data from many sources indicate that urbanization is impacting the Barton Springs segment of the Edwards Aquifer and Barton Springs. These impacts appear to be relatively minor thus far. The consistent presence of tetrachloroethylene in the springs in the late 1980's and early 1990's indicates that human activities, either chronic or catastrophic, can and do impact the springs. Several heavy metals, including arsenic, cadmium, copper, lead, nickel, and zinc, as well as sediment of anthropogenic origin, including fibers and glass, have been detected in Barton Springs. Old Mill and Cold Springs also appear to be affected by urbanization as indicated by detection of heavy metals, pesticides, and total petroleum hydrocarbons. Comparative analysis of transient impacts has not been conducted.

Nutrient levels in Barton Springs are still within apparent background levels based on useful historic data from the early 1980's. Highest nitrate-nitrogen concentrations in the springs are generally greatest during low discharge (<40 cfs) conditions. During 1981-82, nitrate-nitrogen low discharge concentrations averaged 1.54 mg/L compared to 1.46 mg/L during similar conditions in 1995-96.

Many chemical constituents in Barton Springs show a relationship to discharge rate. Nitrate-nitrogen, total nitrogen, sodium, chloride, sulfate, magnesium, fluoride, total dissolved solids, and specific conductance are all inversely related to discharge. Dissolved oxygen, total suspended solids, and bacteria are all directly related to spring discharge rate. Nitrate-nitrogen concentrations display a bimodal distribution of high and low values that inversely correlate with this region's bimodal rainfall distribution, where concentrations are lowest in May, June, October, and November and highest in August, September, December, and January.

Water in the BSEA is classified as calcium-bicarbonate type. Leakage from the Glen Rose Aquifer or from deep Edwards "bad water" can locally alter water to be richer in sodium, chloride, sulfate, and fluoride. Analysis eliminating wells with Glen Rose or Edwards "bad water line" signatures indicates that seven wells and Old Mill Spring appear to be subtly impacted by urbanization as indicated by sulfate, chloride, and nitrate. Most impacted wells are in the northern end of the aquifer where urban development is the densest and oldest. Three wells are in urban areas with either on-site septic systems or past effluent irrigation. These subtle impacts are consistent with changes documented in springs in the Bull Creek watershed. The source of the possible pollution is unknown but may be related to wastewater, either from on site disposal systems or leaking infrastructure lines, irrigation, or other human activities. It is possible that small volumes of water from adjacent aquifers are giving three wells and Old Mill Spring the urban sulfate/chloride signature identified in the Bull Creek watershed. However, the fact that two of these wells have had other health-related water quality problems is suggestive of an urban source of impact.

In-situ data loggers have been extremely valuable in documenting changes in basic water chemistry in Barton Springs, particularly in response to rain events. The magnitude of these changes is related to the magnitude of the rain event. Spring chemistry has several characteristic short-term responses in chemical parameters following rain events. Specific conductance and pH typically decrease following rainfall, whereas turbidity and dissolved oxygen typically increase. Temperature effects are two-fold and related to seasons. Initially, temperature increases following rain events at all times of the year. However, during summer months temperature returns to pre-rain levels and in cooler months it decreases to below pre-rain levels before returning to near pre-rain levels.

Because of the nature of the aquifer with rapid recharge and migration of water, Barton Springs, and presumably the other springs, are affected relatively quickly by runoff from rainfall. Analysis of timing between rainfall and impacts in Barton Springs indicates an average lag time of approximately 14 hours with a range from five to 18 hours. Calculations for storm water velocities in the aquifer based on 14 hours migration time and recharge at various points along Barton Creek indicate velocities ranging from 330 to 1215 ft/hr, averaging 867 ft/hr. The cluster of rainfall responses in the six hour range may result from recharge from a closer location, perhaps in a Barton Hills tributary. Using a Barton Hills tributary as recharge point generates storm water velocities of 660 ft/hr. A single data point suggesting possible recharge from the Williamson Creek watershed subtly affecting Barton Springs in 65 hours indicates storm water velocities ranging from 340 to 450 ft/hr.

The *in-situ* data loggers have also recorded data that provide detail to the internal complexity of the aquifer near Barton Springs. Regular maintenance at Barton Springs pool requires dropping pool water levels approximately 4.5 ft. Several hours following the drop in water levels, a sharp increase in specific conductance occurs. Chemical analysis indicates that the spike represents a slug of water from the bad water zone entering the fresh water zone and discharging from the springs and is characterized by greater sodium and chloride, higher specific conductance, and lower dissolved oxygen.

Based on characteristics of recharge, flow, storage, and variations in chemical properties, the Edwards Aquifer is classified as a very sensitive aquifer. Recorded impacts on Barton Springs from numerous rain events indicate that the spring is most sensitive to events in Barton Creek. This implies that in the future Barton Springs will be more greatly affected by short and long term water quality in Barton Creek than in other contributing creeks. However, chronic water quality problems in other recharging watersheds will also impact the springs and will be a concern for those relying solely on the Edwards Aquifer for drinking water.

2.8 RECOMMENDATIONS

Based on results of this study, discussions with scientists studying the Edwards Aquifer, discussions with State and Federal agency staff, and considering the controversy surrounding topics addressed in this report, the following recommendations are made to help gather data to resolve ground water quality and quantity issues in the Barton Springs watershed:

Barton Springs Contributing Zone

- Continue to identify and sample springs in urban and rural settings to refine observed differences in ground water chemistry and determine possible reasons for changes in ground water chemistry in urban settings.

- Identify and sample springs in developing areas to evaluate changes in ground water chemistry as development progresses.

- Intensify monitoring of springs influenced by wastewater effluent irrigation, including golf courses, to better quantify impacts to ground water chemistry and evaluate role of wet and dry climatic conditions on ground water chemistry.

- Increase monitoring of flow conditions in watersheds with different land uses and impervious cover to refine relationship between area and flow and to determine maximum impervious cover levels that would allow continued high quality and quantity of baseflow in tributaries.

- Use tracer technology, such as optical brighteners, nitrogen isotopes, and ion chemistry to evaluate impacts of alternative wastewater disposal on ground water.

Barton Springs Recharge Zone

- Continue monitoring at Barton Springs for database to evaluate future changes in spring chemistry.

- Begin analyzing suspended sediment discharging from Barton and other springs to establish baseline conditions and determine levels of possible contaminants attached to sediments.

- Increase monitoring of heavy metals in Barton and other springs to evaluate possible urban influence.

- Increase use of *in-situ* multiprobe data recorders in Barton and other springs to establish baseline conditions and baseline response to rain events.

- Continue collecting storm water samples from Barton Springs to determine storm water runoff effects on spring chemistry. Use storm data to establish characteristic turbidity (and total suspended solids) response in Barton Springs to different rainfall amounts under various aquifer water levels and flow rates in Barton Creek. Use mass balance calculations to evaluate storm water runoff volumes and related water chemistry changes in BSEA springs.

- Determine timing of storm water runoff impacts in other BSEA springs (Old Mill, Eliza, Cold, Backdoor). Collect storm water runoff samples from springs to determine effects on spring chemistry.

- Collect samples from Barton and other springs and wells during pool drawdown to verify source of high conductance water and evaluate impacts to spring chemistry to help estimate potential effects on salamander biology.

- Measure flow rates in Barton Creek over Recharge Zone to determine recharge rates for specific creek segments under different aquifer water levels. Also measure flow rates in Eanes Creek to determine recharge rate for this unmeasured recharge creek which will help quantify short flow paths to Cold Springs and Town Lake.

- Continue with tracer studies in BSEA to determine ground water velocities from various recharge points, to verify relationship between recharge points and wells and springs and to evaluate sensitivity of specific creek segments to potential contamination. Support future tracer efforts in BSEA.

- Initiate discussions to locate new well to monitor BSEA water levels in near Barton Springs for use in establishing discharge rates from Barton and associated springs. The new well must be minimally affected by pool drawdowns.

- Deepen USGS monitoring well YD-58-42-217 (Loop 360) to allow sampling during low water levels in aquifer.

- Refine estimates of aquifer water levels where flow continues in Old Mill and Eliza Springs while Barton Springs Pool is lowered to aid protection of the Barton Springs Salamander, reduce threats, and reduce staff time to monitor these springs during pool drawdown.

3.0 SURFACE WATER STUDIES

3.1 INTRODUCTION

Staff from the City's Environmental Resources Management Division (ERM) monitors surface water quality in the Barton Creek Watershed by comparing physical, chemical, and biological differences between perennial pools along the mainstem of the creek and among a number of tributaries influenced by various land uses. Monitoring is performed to characterize overall water quality in Barton Creek , to determine baseline water chemistry in rural areas, and to determine the effects of urbanization on surface water and sediment quality. These studies concentrate on Barton Creek above (west of) the Edwards Aquifer Recharge Zone, before Edwards Aquifer spring water begins to enter the system.

3.2 POOLS STUDY

3.2.1 Preface

In 1979, Espey Huston and Associates (EH&A) prepared a report entitled *The Barton Creek Watershed Study* for the City of Austin's Office of Environmental Resources Management in which they concluded "Additional studies are urgently needed on nearly every aspect of the Barton Creek Watershed ecosystem." EH&A specifically recommended the following ecological investigation: "The aquatic communities of the permanent pools and stream segments in upstream areas should be carefully studied during "dry" seasons, when they are isolated from downstream segments, to determine to what extent, if any, they differ from the permanent downstream segments."

The Austin City Council passed a resolution on October 15, 1987 which directed the Department of Environmental Protection to assist the Environmental Board in a full scale review and analysis of the Barton Creek Watershed. One of the main goals of the Austin community as summarized in the *Barton Creek Policy Definition Report* (BCPDR) is as follows:

"To maintain existing surface water quality in Barton Creek , its tributaries, and pools." This report goes on to recommend the following action: "Continue to monitor and report upon changes in baseline conditions of land and water resources in the watershed (Barton Creek) which are attributable to urban development."

High quality abundant baseflow is critical to the maintenance of aquatic habitat and the recreational value of Barton Creek, and to water quality of the Edwards Aquifer and Barton Springs. In fact, baseflow makes up approximately 75 percent of the total flow occurring in the creeks contributing to the Barton Springs Edwards Aquifer, and 86% of the total recharge to the aquifer originates as baseflow (Santos, Loomis, & Assoc., 1994). In 1990, ERM initiated a long term, more comprehensive baseflow water quality study and an ecological assessment of pools along the mainstem of Barton Creek.

ERM monitors baseflow water chemistry and percent cover of filamentous algae growth at nine natural pool sites on the mainstem of Barton Creek, from the headwaters, above Dripping Springs, to the Edwards Aquifer Recharge Zone, above the Loop 360 bridge in Austin. Quantification of each pool's benthic vegetative cover focused principally on filamentous algae cover, because fast growing algae quickly respond to nutrient enrichment (Stevenson and Lowe 1986, Hynes 1970) and, in persistent dense populations, is regarded as a detriment to the aquatic ecology, recreational value, and beauty of Barton Creek.

Although other sites on Barton Creek were monitored for water chemistry in the Recharge Zone, the influence of Edwards Aquifer recharge features and spring water entering the system in these areas prevents a spatial comparison of water quality with sites above the Recharge Zone along Barton Creek. The Glen Rose geologic formation governs springs and seeps contributing baseflow to the nine pools compared in this report; therefore, the influence of geology on water chemistry is fairly homogeneous.

3.2.2 Methods

3.2.2.1 Site Selection

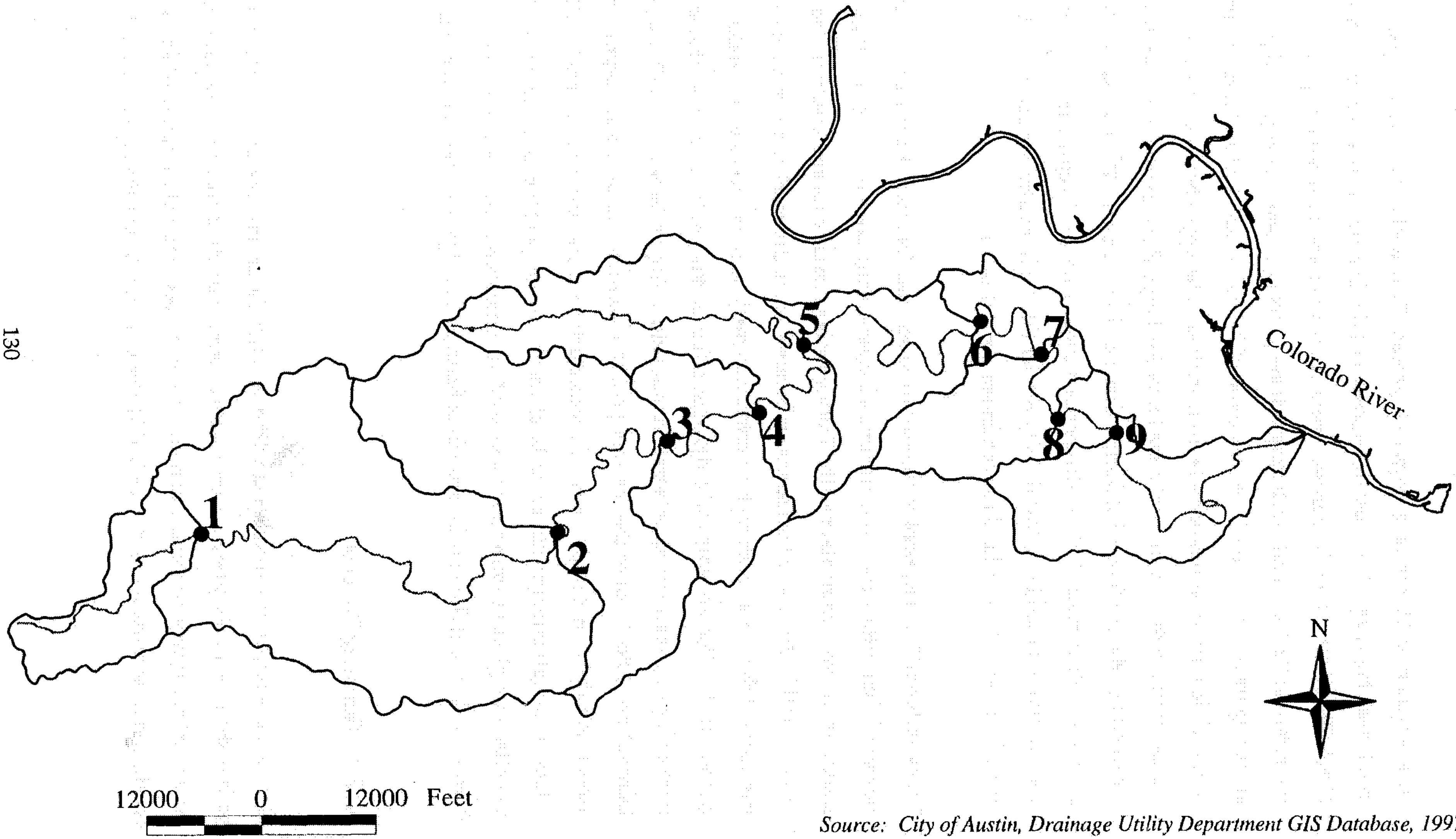
The study area includes relatively undeveloped and rural reaches of Barton Creek from the headwaters near Dripping Springs to Highway 71, as well as more developed reaches of the creek from Highway 71 to just downstream of the Campcraft Road access to the Barton Creek Greenbelt. Site selection was made from a number of accessible points along the mainstem of Barton Creek, including private property, road crossings, and public greenbelt areas (Figure 3.1 and Plate 2). A minimum of 2.2 miles (3.57 km) and a maximum of 6.6 miles (10.48 km) separates one site from another. The upper headwater site is 43.9 miles (70.25 km) from the mouth, while the lower Recharge Zone site is 6.3 miles (10.01 km) from the mouth or the confluence of Barton Creek and Town Lake. The nine sites selected each drain a sizable portion of the entire Barton Creek Watershed, representing a variety of land uses including ranch land, low density residential, high density residential, golf courses, green belts, and various land use combinations (Table 3.1).

Pools within riffle/run/pool complexes were selected for study, because pools are more perennial than riffles and runs, creating a longer-lasting aquatic environment for use as indicators of environmental health. During reconnaissance for site selection, the nine pools elected for this study were conspicuous because of the dry creekbed prevalent in riffle and run areas at this time. Although an effort was made to select pools with similar characteristics, flood events had a dynamic effect on the pools, sometimes changing their morphology by rearranging substrate composition. Appendix Section A (Physical Description of Pools) describes various pool characteristics such as size, depth, volume, aspect, and riparian canopy cover. Overall, during the five years of this study, all nine sites retained enough integrity always to be characterized as pool habitat, and the pools maintain a similar enough environment to be viewed as comparable sites for collection of water chemistry data and data on the growth of filamentous algae or other aquatic vegetation.

3.2.2.2 Sampling Protocol

Grab water samples were collected within an eight-hour time period by ERM staff from each of the nine pools quarterly, once each season. Standard collection methods were employed to prevent contamination and insure preservation of samples; all analyses were conducted in accordance with *Standard Methods For the Examination of Water and Wastewater*

Figure 3.1
Barton Creek Pool Study Sites



Source: City of Austin, Drainage Utility Department GIS Database, 1997

Table 3.1
Barton Creek Pools Study
Impervious Cover and Land Use Types

Site Number	Intervening Drainage Area Acres	Acres Impervious Cover	Percent Impervious Cover	Cumulative Acres	Cumulative Impervious Cover Acres	Cumulative Impervious Percent
1	3974.49			3974.49		
2	23150.09	14.493	0.06	27124.58	14.493	0.05
3	14485.36	684.527	4.73	41609.94	699.020	1.68
4	6024.44	339.884	5.64	47634.38	1038.904	2.18
5	9692.1	775.598	8.00	57326.48	1814.502	3.17
6	5104.82	405.784	7.95	62431.3	2220.287	3.56
7	2148.51	243.662	11.34	64579.81	2463.949	3.82
8	4402.38	392.346	8.91	68982.19	2856.294	4.14
9	985.48	125.269	12.71	69967.67	2981.563	4.26

Land Use (Acres)

Site Number	Vacant	Parks & Golf	Single Family	Mobile Home	Multi-Family	Office	Commercial	Industrial	Trans-portation	Utilities	Civic/ Educational	Undeter-mined
1												3974.49
2	122.75		27.85									22999.50
3	11206.03	22.25	392.75				0.75	8.07				2855.52
4	5875.61		143.97					4.85				
5	8831.75		528.71			3.01	38.84	69.21	82.25	52.81	85.50	
6	4642.67	32.53	235.21					28.96	63.50	9.651	92.32	
7	1648.58	99.99	268.94			19.05	7.92	47.66	25.24	0.44	30.70	
8	3199.28	535.67	610.50		21.24		2.85		2.43	0.12	30.31	
9	691.88		279.67			9.40				4.53		

Source: City of Austin, Drainage Utility Department GIS Database, 1997

(Appendix C). Parameters measured in the laboratory included: nitrate+nitrite nitrogen, total Kjeldahl nitrogen, ammonia nitrogen, total nitrogen, orthophosphate as P, total phosphorus, total suspended solids, volatile suspended solids, and fecal coliform. Fecal streptococcus, total organic carbon, biochemical oxygen demand, and chemical oxygen demand were measured at selected sites and times as well. Dissolved oxygen, specific conductance, pH, and temperature were measured in the field with a Hydrolab Surveyor II. Total dissolved solids and turbidity were measured in the field with a Hach TDS pen and a Hach Model 16800 turbidimeter respectively. The Hydrolab, TDS pen, and turbidimeter were calibrated according to instrument instructions at the beginning of each field day.

Other information such as flow, air temperature, last rainfall, and existing weather conditions were measured or noted on field sheets for each collection event. Flow was measured using methods recommended by TNRCC's 1993 *Water Quality Monitoring Procedures Manual*, on two occasions early in the study, during the spring of 1991, using a Montedoro Whitney Model PVM-2A Velocity Meter. Flow was added as a regular parameter in February of 1995, using a Marsh McBirney Model 2000 Velocity Meter. Air temperature was taken at each site with a standard centigrade thermometer, and other weather conditions such as relative wind and cloud cover were noted on the data sheet.

ERM staff collected water samples during baseflow conditions, defined as follows: at least 12 hours following measurable precipitation of less than 0.5", at least 24 hours following a rainfall of between 0.5" and 1.0", and at least 48 hours following a rainfall of greater than 1.0". The definition of baseflow is consistent when describing sampling conditions throughout this study section.

3.2.2.4 Aquatic Vegetation Benthic Cover

Percent cover was measured with a standard plant ecology technique using line transects. H.L. Bauer developed the line intercept method in 1943 for measuring plant cover by reducing a quadrat to a single dimension or line (Barbour, 1980, *Terrestrial Plant Ecology*). Blum (1957) was the first to apply this transect method to stream algae, and Hynes (1970) suggested that the method gives results closely resembling the actual status of the flora in the stream, and worthy of further use and refinement. The distance that all plants or unvegetated substrates project through the plane of the line is tallied. The total fraction of the line or lines covered by each category of cover, multiplied by 100, is equal to that category's percent cover. Each pool was divided by three to six equally-spaced transects; the number of transects depended on the length of the pool.

Aquatic vegetative cover was measured during the same week that quarterly water samples were collected. One ERM staff person, experienced in identification of all common aquatic plant types, identified the number of feet covered by each encountered plant or exposed substrate along multiple transects in all nine pools. All aquatic vascular macrophytes were identified to the genus level using Correll and Correll (1972) as a reference; non-filamentous algae with macrophyte morphology such as *Nitella* sp. and *Chara* sp. were identified by genus; commonly encountered spongy composites of blue-green algae, diatoms, and sediment were identified as "carpet algae"; filamentous algae were categorized as *Cladophora* sp. or *Spirogyra* sp. "type" depending on their texture and branching habit; all blue-green algae were lumped together, and unvegetated substrates were identified as one of seven categories. Five categories of unvegetated substrate were characterized by particle size according to Compton's *Geology in the Field* (1985), and the other two unvegetated substrates were characterized as bedrock and leaf litter (included any dead or decomposing organic matter). Altogether, 26 commonly encountered categories of cover were listed on the field data sheet; several blank columns were available for the addition of rarely encountered plants or substrates. These categories were lumped into four super categories for analysis purposes: unvegetated substrate, filamentous algae, nonfilamentous algae, and aquatic macrophytes.

Cladophora sp. algae is coarse in texture and is multi-branched in morphology, making field identification of this genus rather easy. Dr. Richard Starr, University of Texas at Austin Phycologist, verified field collections of *Cladophora* for ERM staff. However, other non-branching, slimy textured algae, identified as *Spirogyra* "type" on the data sheet, usually were a *Spirogyra* sp. or belonged to other genera in the *Spirogyra* sp. family, Zygnemataceae, including *Sirogonium* sp., *Mougeotia* sp. and *Zygnema* sp. (Bold, H.C., *Introduction To The Algae,* 1985). Differentiation of these genera was difficult in the field, and sometimes microscopic identification revealed that these slimy filamentous populations were combinations of one or more Zygnemataceae genera. For the purpose of this study, our task was simply to measure the cover of filamentous green algae and differentiate *Cladophora* from members of the Zygnemataceae family. This distinction was made because *Cladophora* is perceived as more of a nuisance species when dominant than the other more ephemeral members of the Zygnemataceae family.

3.2.2.5 Quality Assurance and Quality Control (QA/QC)

Quality assurance measures included proper instrument calibration before each sampling event, laboratory cleaned and approved sample containers, appropriate preservation and storage temperatures, adherence to required holding times, documentation between field and lab personnel through a chain of custody form, and labels with site, date, parameters, and preservation methods clearly indicated. Copies of laboratory data sheets, as well as field parameter and flow data sheets were kept on file. All data were entered into a database and verified by ERM staff before they were used in analysis and reports.

Analytical quality control for water chemistry parameters was assessed by measuring accuracy and precision. Blind duplicates or splits were submitted for 10 percent of all samples analyzed, and one blind field standard set was submitted by ERM. Lab duplicates, blanks, calibration standards, and appropriately concentrated blind standards were regularly analyzed at the City of Austin's Walnut Creek Wastewater Laboratory as part of their internal QA/QC. Records of all quality control information were reviewed to make improvements during the course of the study.

Quality assurance and consistency were maintained for the measurement of aquatic plant percent coverage by using one ERM staff person, trained in the identification of aquatic plants, to determine the distances of coverages at all pools during any one quarterly inventory. Percent cover data sheets were kept on record, entered into a database, and verified by ERM staff before being used in analysis and reports.

3.2.2.6 Analyses For Statistical Significance

Several tests were conducted on the parameter concentrations. Analysis of variance was conducted using the General Linear Models (GLM) procedure in SAS since it is appropriate for unbalanced data sets. A probability of 0.05 or less is considered significant. In some situations instrument accuracy should be considered regardless of the statistical results. This is especially important with parameters measured near the detection limit or when instrument resolution is less than the statistical difference. Values below reporting limits were substituted at half the detection limit in calculation of summary statistics and hypothesis testing. Even with these limitations, the statistical analysis is an early indicator of subtle differences that may become more conspicuous at higher levels of development.

The procedures were as follows:

1. Test the data for normality.
2. Rank the non-normal data when the parameters tested are not normally distributed.
3. Conduct an analysis of variance for significantly different means on the rankings. This is equivalent to a non-parametric test for differences between the means. If the test indicates significantly different means, conduct comparison tests. Use contrast statements to provide customized hypothesis tests for the ranked data.
4. Use non-parametric Kruskal-Wallis Test for comparison of the GLM test on the ranked data, with the same results.
5. Use a non-parametric Median Analysis on the medians.
6. Alternate handling of non-detect data was examined by censoring the data at the detection limit and conducting the nonparametric tests described above using the censored data (Helsel, 1990).

3.2.3 Results

ERM staff began the study of Barton Creek pools in November of 1990, beginning with characterization of the pools' morphology and initial determination of aquatic plant percent cover. Flow, Hydrolab, TDS pen, and fecal coliform parameter values were also obtained at this time. Sampling all sites within a single day and analysis of additional laboratory parameters at the City's Walnut Creek Laboratory began in March of 1991.

Means, medians, maximums, and minimums were determined for each water chemistry parameter at every site (Table 3.2). Since the data set for the nine study pools is relatively small (usually less than 20 points per parameter per site), median values are considered closer to the "true" representative number or concentration characterizing parameters at a given site. Since the median value is simply the number that falls in the middle position of a data set, the median is not as influenced by outliers as a mean (Sokal et al., 1995). Comparisons made among pools in this study illustrate some small but statistically significant spatial differences in water quality along Barton Creek's mainstem; however, various statistical analyses attempting to show temporal trends proved insignificant.

Comparisons were made between this study's results and the baseline geometric means which were tabulated using data collected between 1978 and 1986 at Loop 360 and Barton Creek for the 1988 Barton Creek Policy Definition Report (BCPDR). A comparison of results was made with Texas Water Commission's (now TNRCC) *Texas Aquatic Ecoregion Project, An Assessment of Least Disturbed Streams* (1992), in which the water quality of six selected unclassified streams was determined for each of 12 Texas ecoregions. A comparison of averages from the Central Texas Plateau Ecoregion was done. One of the six creek sites included in this ecoregion was Barton Creek at the Barton Creek West Subdivision, a site located between Pools 5 and 6 of ERM's study. This site and others in the Central Texas Plateau Ecoregion were monitored during low baseflow conditions by TNRCC in summer of 1988, and provide a good baseline water chemistry profile for comparison with ERM's

Table 3.2

Barton Creek Pools Study
Baseflow Conditions

Site		Temperature °C	pH	Conductivity (umhos/cm)	TDS (mg/L)	Turbidity (ntu)	TSS (mg/L)	VSS (mg/L)	Fecal Coliform (col /100 mL)	Fecal Streptococcus (col/100 mL)	DO (mg/L)
Pool 1	count	19	21	18	19	21	17	17	18	2	17
Pool 1	minimum	9.56	6.68	331	190	0.37	0.25	0.25	23	101	4.74
Pool 1	maximum	29.00	8.00	605	330	4.70	8.00	4.00	1416	267	12.25
Pool 1	mean	19.32	7.63	548	241	1.27	2.09	0.88	238	184	8.28
Pool 1	median	18.88	7.65	560	230	0.70	2.00	0.50	85	184	8.37
Pool 2	count	19	21	18	20	19	17	17	18	2	17
Pool 2	minimum	11.07	6.69	393	150	0.19	0.25	0.25	0	28	6.42
Pool 2	maximum	33.00	8.34	593	280	4.40	8.00	2.00	480	72	10.80
Pool 2	mean	21.06	7.79	513	222	1.97	2.10	0.64	74	50	8.78
Pool 2	median	19.99	7.83	521	220	1.70	1.70	0.25	25	50	8.72
Pool 3	count	19	19	17	18	19	17	17	16	0	17
Pool 3	minimum	10.63	6.82	360	130	0.20	0.25	0.25	5		6.00
Pool 3	maximum	32.30	8.40	594	280	3.00	4.00	1.00	271		11.25
Pool 3	mean	21.22	7.82	494	215	1.04	1.24	0.45	63		8.62
Pool 3	median	19.96	7.83	506	220	0.85	1.00	0.25	30		8.85
Pool 4	count	19	19	17	19	19	17	17	16	0	17
Pool 4	minimum	9.04	6.81	433	160	0.21	0.25	0.25	7		4.80
Pool 4	maximum	29.95	8.17	577	300	5.40	2.00	2.00	876		11.75
Pool 4	mean	19.85	7.71	503	221	1.15	1.04	0.70	86		8.24
Pool 4	median	19.54	7.75	495	220	0.53	1.00	0.60	27		8.38
Pool 5	count	19	20	18	18	21	17	17	18	2	17
Pool 5	minimum	12.48	6.96	428	160	0.15	0.25	0.25	0	72	5.71
Pool 5	maximum	32.80	8.32	566	250	4.80	8.30	4.00	624	332	10.80
Pool 5	mean	21.19	7.84	492	208	1.33	2.80	0.79	100	202	8.74
Pool 5	median	20.58	7.82	489	210	0.75	1.60	0.50	24	202	8.92
Pool 6	count	19	18	16	19	19	17	17	17	0	16
Pool 6	minimum	12.34	7.19	230	190	0.15	0.25	0.25	0		7.00
Pool 6	maximum	32.10	8.24	644	377	3.80	4.00	3.00	60		11.04
Pool 6	mean	21.72	7.82	504	230	0.84	1.24	0.46	15		9.16
Pool 6	median	20.46	7.79	522	220	0.55	0.60	0.25	6		9.17
Pool 7	count	19	19	15	18	19	17	17	16	0	17
Pool 7	minimum	10.53	7.46	440	190	0.36	0.25	0.25	0		7.06
Pool 7	maximum	33.45	8.10	777	340	7.60	12.00	3.00	456		12.91
Pool 7	mean	21.21	7.80	554	227	2.27	2.56	0.76	46		9.60
Pool 7	median	20.21	7.80	532	220	1.50	1.00	0.25	12		9.12
Pool 8	count	19	17	18	17	18	17	17	17	2	17
Pool 8	minimum	12.21	7.36	477	200	0.48	0.25	0.25	4	37	6.70
Pool 8	maximum	33.93	8.10	1002	460	4.80	6.00	2.00	492	107	13.56
Pool 8	mean	21.07	7.81	602	268	1.87	1.93	0.66	81	72	9.96
Pool 8	median	20.44	7.83	548	250	1.60	1.25	0.30	24	72	10.50
Pool 9	count	19	19	17	19	19	17	17	16	0	17
Pool 9	minimum	12.07	7.27	476	180	0.27	0.25	0.25	0		4.56
Pool 9	maximum	32.15	8.21	850	380	5.40	16.00	5.00	143		11.95
Pool 9	mean	21.63	7.76	553	239	2.27	4.11	0.97	32		8.69
Pool 9	median	20.50	7.82	527	230	1.70	2.00	0.25	7		9.00

Source: COA / DUD Database 1990 - 1995

Table 3.2 Continued

Barton Creek Pools Study
Baseflow Conditions

Site		NO3/2-N (mg/L)	NO2-N (mg/L)	NH3-N (mg/L)	TKN (mg/L)	TN (mg/L)	Total Phosphorus (mg/L)	Ortho-P (mg/L)	TOC (mg/L)	BOD (mg/L)	COD (mg/L)	Flow (cfs)
Pool 1	count	14	1	18	15	29	17	14	0	0	7	5
Pool 1	minimum	0.01	0.025	0.01	0.05	0.06	0.01	0.01			2.50	0.07
Pool 1	maximum	0.13	0.025	0.10	0.52	0.65	0.07	0.02			14.00	2.94
Pool 1	mean	0.05	0.025	0.03	0.22	0.26	0.02	0.01			5.27	1.38
Pool 1	median	0.04	0.025	0.02	0.20	0.24	0.01	0.01			2.50	0.99
Pool 2	count	14	1	19	16	30	17	14	0	0	6	5
Pool 2	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01			2.50	0.71
Pool 2	maximum	0.21	0.025	0.12	0.61	0.82	0.08	0.07			10.20	11.15
Pool 2	mean	0.06	0.025	0.03	0.23	0.28	0.02	0.02			4.62	5.44
Pool 2	median	0.04	0.025	0.02	0.20	0.23	0.01	0.01			3.75	4.24
Pool 3	count	14	1	17	16	30	17	14	0	0	5	5
Pool 3	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01			2.50	4.83
Pool 3	maximum	0.21	0.025	0.08	0.53	0.74	0.24	0.14			18.30	24.72
Pool 3	mean	0.07	0.025	0.03	0.17	0.24	0.04	0.03			7.66	12.44
Pool 3	median	0.04	0.025	0.02	0.12	0.16	0.02	0.01			5.00	10.97
Pool 4	count	14	1	17	16	30	17	14	0	0	6	5
Pool 4	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01			2.50	6.74
Pool 4	maximum	0.21	0.025	0.09	0.69	0.90	0.05	0.02			7.00	33.07
Pool 4	mean	0.06	0.025	0.03	0.23	0.30	0.03	0.01			4.37	19.83
Pool 4	median	0.04	0.025	0.02	0.16	0.20	0.02	0.01			3.75	15.25
Pool 5	count	14	1	19	16	30	17	14	12	1	12	5
Pool 5	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01	1.37	0.50	2.50	5.13
Pool 5	maximum	0.21	0.025	0.14	0.60	0.81	0.05	0.01	18.50	0.50	9.00	25.57
Pool 5	mean	0.07	0.025	0.03	0.21	0.28	0.02	0.01	6.18	0.50	3.46	15.27
Pool 5	median	0.04	0.025	0.02	0.17	0.21	0.01	0.01	2.75	0.50	2.50	14.78
Pool 6	count	14	1	17	16	30	17	14	0	0	6	5
Pool 6	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01			2.50	4.37
Pool 6	maximum	0.20	0.025	0.08	0.63	0.83	0.65	0.28			13.20	28.03
Pool 6	mean	0.08	0.025	0.03	0.19	0.26	0.05	0.03			4.70	17.88
Pool 6	median	0.07	0.025	0.03	0.13	0.19	0.01	0.01			2.50	19.79
Pool 7	count	14	1	17	16	30	17	14	0	0	5	5
Pool 7	minimum	0.02	0.025	0.01	0.07	0.08	0.01	0.01			2.50	5.92
Pool 7	maximum	0.44	0.025	0.08	0.54	0.98	0.04	0.10			11.30	29.26
Pool 7	mean	0.10	0.025	0.03	0.23	0.34	0.02	0.02			5.26	16.31
Pool 7	median	0.07	0.025	0.03	0.20	0.27	0.02	0.01			5.00	18.20
Pool 8	count	14	1	19	16	30	17	14	12	1	12	5
Pool 8	minimum	0.02	0.025	0.01	0.12	0.14	0.01	0.01	1.77	0.50	2.50	4.98
Pool 8	maximum	2.48	0.025	0.10	0.72	3.20	0.08	0.07	32.70	0.50	8.50	31.21
Pool 8	mean	0.31	0.025	0.03	0.31	0.62	0.03	0.02	7.95	0.50	4.00	19.83
Pool 8	median	0.15	0.025	0.03	0.23	0.38	0.02	0.01	3.59	0.50	2.50	23.99
Pool 9	count	14	1	17	16	30	17	14	0	0	6	5
Pool 9	minimum	0.02	0.025	0.01	0.05	0.07	0.01	0.01			2.50	1.44
Pool 9	maximum	0.20	0.025	0.10	0.70	0.90	0.09	0.06			5.00	47.68
Pool 9	mean	0.09	0.025	0.03	0.20	0.29	0.02	0.02			3.75	25.06
Pool 9	median	0.09	0.025	0.03	0.16	0.25	0.02	0.01			3.75	29.30

Source: COA / DUD Database 1990 - 1995

study of the nine Barton Creek pools. Findings from ERM's study were also compared with data collected by the City of Austin's Water Watchdog Program, which has monitored and indexed the water quality of nine streams contributing to Town Lake at their mouth, including the mouth of Barton Creek, from 1990 to the present.

Nineteen aquatic plant taxa and seven unvegetated substrate types were encountered and used to characterize the benthic cover of the nine study pools. A list of these plants and substrates with their overall average percent cover throughout the watershed is shown in Table 3.3. This cover is lumped into four broad categories, and a five year average cover at each pool is charted for the following: unvegetated substrates, aquatic macrophytes, filamentous algae, nonfilamentous algae. The focus of the percent cover survey was a comparison and quantification of filamentous algae cover at each of the pools. Significant differences were found in the average percent cover of filamentous algae in the nine pools over the five year study period, and there were also positive correlations between filamentous algae cover and concentrations of nitrate-nitrogen.

Following the statistical analysis procedure, none of the parameters tested were found to be normally distributed. The median is considered to be a more representative measure of location than the arithmetic mean because it is not affected by extreme values (Sokal et al., 1995). Therefore, analyses for both medians and means were included for reference. Results showed that there were significant differences for the medians of the same parameters whose means were significantly different when tested with the GLM and Kruskal-Wallis tests. Therefore, charts used in this report to visually display data may incorporate means and/or medians, whichever shows the clearest distinction. Parameters with non-normal distributions that have statistically significant differences are conductivity, total dissolved solids, turbidity, total suspended solids, TKN, nitrite/nitrate nitrogen, fecal coliform, flow, and filamentous algae cover. An overview of the statistically significant results for each parameter is presented in Table 3.4 . Appendix H provides details supporting the statistical analysis summarized in Table 3.4. Using the data censored to the highest detection limit, the conclusions of the non-parametric comparison tests remain the same with the exception of TKN and COD. These parameters had variable detection limits with a minority of

Table 3.3
Barton Creek Pools Study
Percent Cover Mean Values

Unvegetated Substrate	SILT (<1/16MM)	9.28
	SAND (1/16-2)MM	2.18
	PEBBLE (2-64)MM	8.92
	COBBLE (64-256)MM	1.86
	BOULDER (>256MM)	2.17
	BEDROCK	15.44
	LEAF LITTER	6.70
Non-Filamentous Algae	ALGAE, CARPET	24.26
	CHARA	5.77
	ALGAE, BLUE-GREEN	0.15
	NITELLA	2.42
Filamentous Algae	CLADOPHORA	2.33
	ALGAE, OTHER	0.09
	SPIROGYRA	8.91
Vascular Macrophytes	BACOPA	0.44
	CAREX E.	0.24
	PHYLA	<0.01
	JUSTICIA	2.50
	LUDWEGIA	0.35
	MYRIOPHYLLUM	0.05
	NAJAS	0.13
	HYDROCOTYL	0.07
	POTOMOGETON	0.12
	ELEOCHORIS	<0.01
	TYPHA	0.00
	UTRICULARIA	3.55

TOTAL AVERAGES	Filamentous Algae	11.33
	Non-filamentous	32.60
	Vascular Macrophytes	9.60
	Substrate	46.55

Source: COA / DUD Database 1990 - 1995

Table 3.4

Barton Creek Pools Study
Overview of Statistically Significant Variables
Baseflow Conditions

Nonparametric Tests	
Tests	**Parameters**
Kruskal Wallis (Means) Test Median Analysis Test (SAS NPARWAY1 Procedure)	Conductivity, TDS, Turbidity, NO3/2-N, Fecal Coliform

Contrast Multiple Comparison Test (SAS GLM Procedure)	
Pools	**Parameters**
8 vs 1-7, 9	Conductivity, TDS, NO3/2-N, TKN
7,9 vs 1-6, 8	Turbidity
9 vs 1-8	TSS
1 vs 2-9	Fecal Coliform
1 vs 2-8	Flow
6 vs 1-5, 7-9	Turbidity

Source: COA /DUD Database 1990 - 1995

relatively high detection limits compared to the data set and the average detection limit. For this reason, the alternate method of handling nondetect data was unreliable for these parameters compared to substituting half the detection limit for nondetects.

3.2.4 Discussion of Results

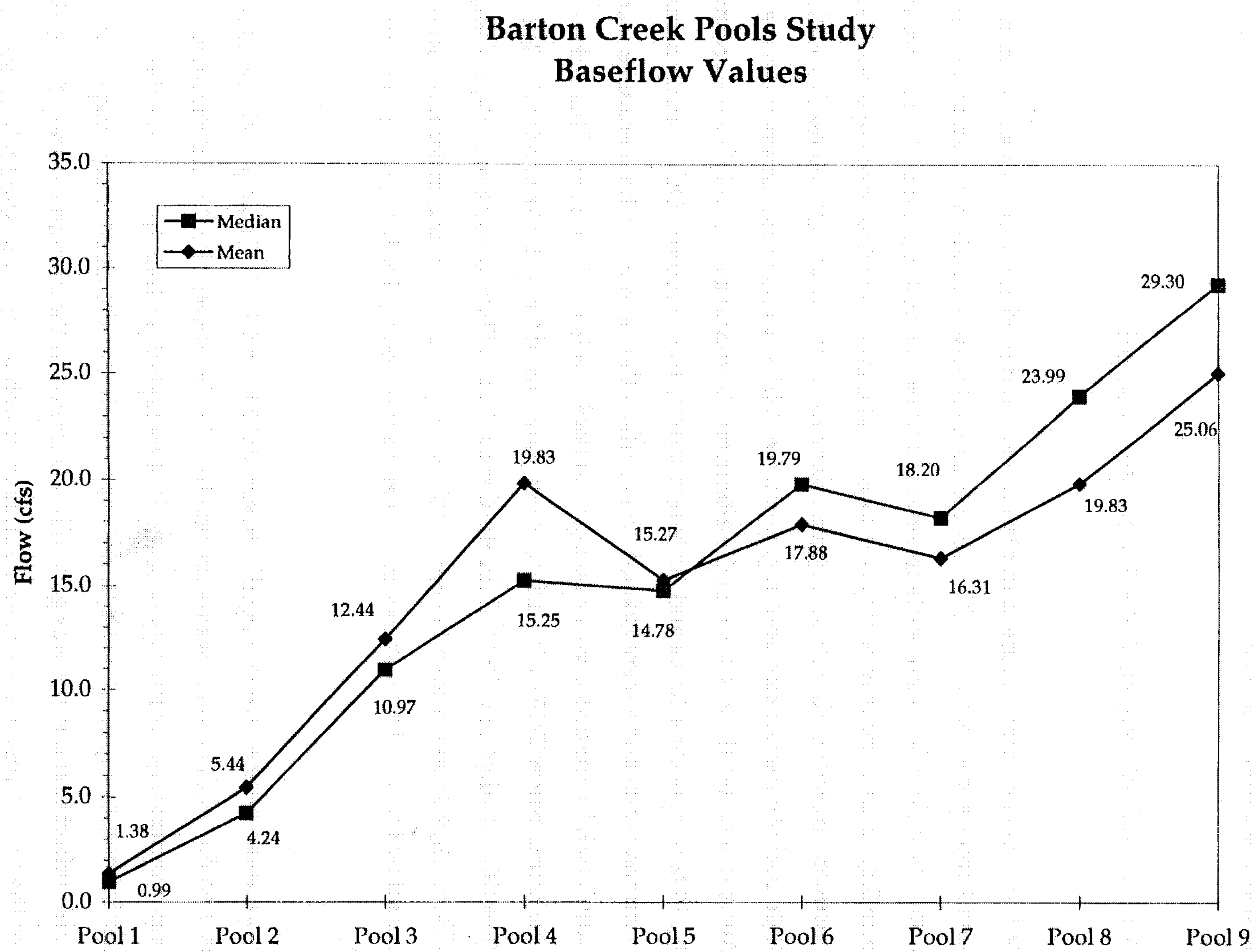
3.2.4.1 Flow

All flow measurements and water collections were made during periods of baseflow as defined in Section 3.2.2. Most measurements and collections were obtained after a period of over 72 hours without measurable precipitation.

Flow was measured five times at all pool sites from 1991 through 1995, representing low as well as high baseflow periods. Average flows at each pool tended to increase from upstream to downstream and ranged from 1.38 cfs at Pool 1, near the headwaters, to 25.06 cfs at Pool 9, just above the Recharge Zone. An average of measurements indicates that baseflow increases 0.63 cfs per mile (.39 cfs per kilometer), characterizing Barton as a gaining creek. Figure 3.2 illustrates the incremental increases in flow from upstream to downstream. Differences in flow among the nine pool sites were significant. The lowest flow recorded in this study was 0.07 cfs at Pool 1 and the highest flow of 47.68 cfs was measured at Pool 9 (Appendix Photos 9A and 9B).

Flows measured by ERM staff were relatively close to flow measurements recorded at the USGS stations (Pools 5 and 8) on the same dates (USGS, Water Resources Data, 1992-94). While the median baseflow calculated with ERM's five measurements is a reasonable median value for this five year study period, a more accurate representation of average baseflow would include a flow measurement for all sampling events in this study rather than the average of the five events shown in Figure 3.2. The average baseflow for all 20 sampling events, as measured by USGS at Pool 8 is 58 cfs, while the average at Pool 8 for the five events measured by ERM staff is 19.83 cfs. This higher USGS average is a result of some high baseflow sampling events following the December floods of 1991. For instance, the

Figure 3.2



Source: COA /DUD Database 1990 - 1995

highest of the five discharges measured by ERM was 47.68 cfs, and the highest baseflow discharge measured by USGS at Pool 8 during any of our 20 sampling events was 390 cfs on 6/4/92 (USGS, 1992). Rates of baseflow and the concentration of constituents such as nitrates are not correlated ($R^2 = 0.053$). An analysis of flow as it relates to pool site drainage area was discussed in Section 2.3.

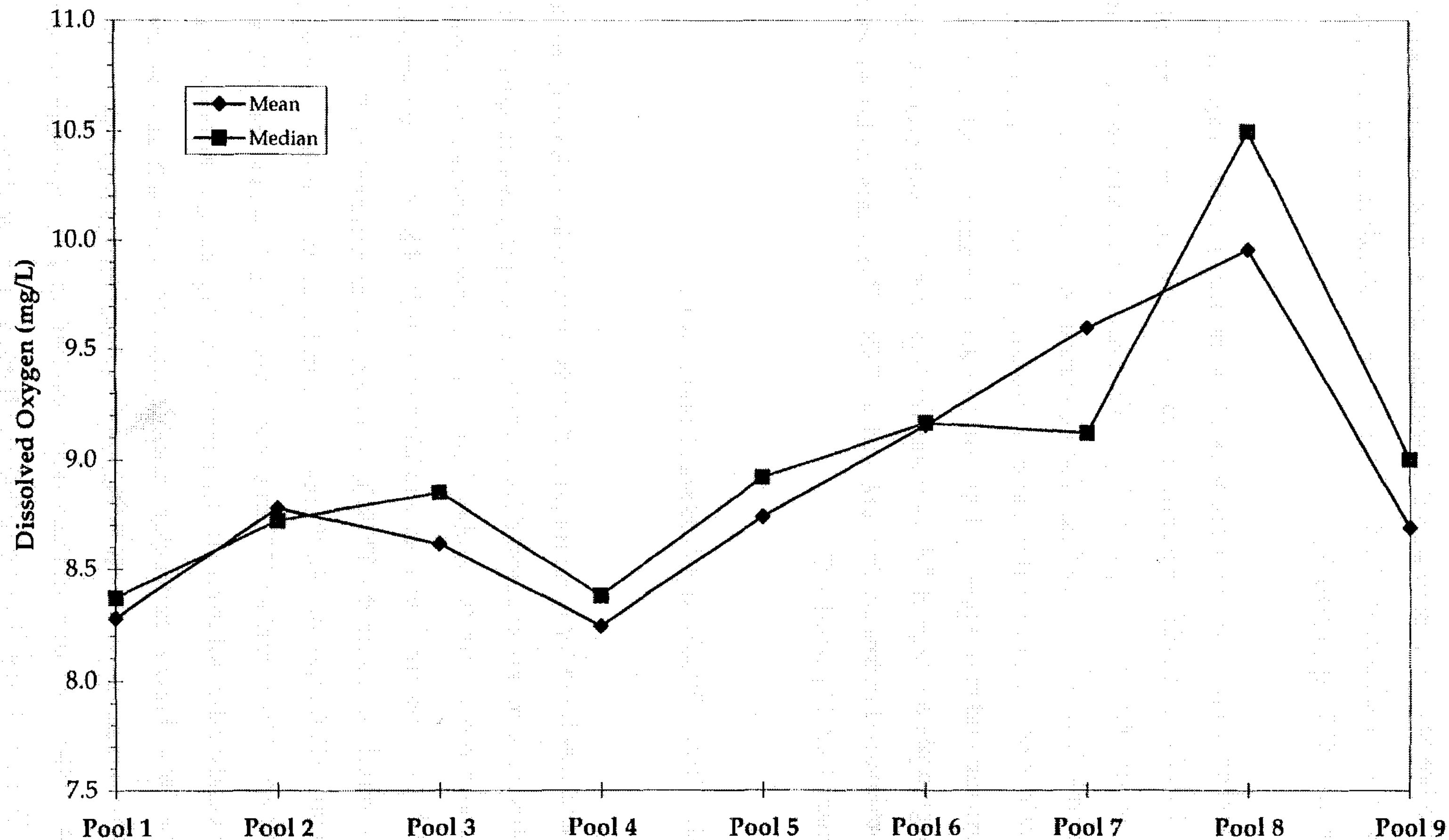
3.2.4.2 Dissolved Oxygen, Water Temperature, and pH

Dissolved oxygen, temperature, and pH averages and medians were not significantly different among the nine sites. DO averages ranged between 8.25 mg/L and 9.96 mg/L, with means and medians generally increasing somewhat from upstream to downstream (Figure 3.3). This trend is probably due to gradual increases in flow from upstream to downstream; however, dissolved oxygen values fluctuated diurnally, increasing with more sunlight and photosynthesis; and in general, the field analysis began upstream in the morning and ended downstream in the afternoon. Seasonal trends in DO were common, owing to corresponding flows and air temperatures, and minimum DOs usually occurred in late summer when pools were isolated from surface flow and water temperatures increased. The minimum DO recorded was 4.56 mg/L at Pool 9 in late July of 1995. This is the only DO measured below TNRCC's surface water standard of 5 mg/L (Appendix E). The average DO calculated by TNRCC for the Central Texas Plateau ecoregion was 6.7 mg/L. This DO is slightly lower than the nine pools' average range, but this difference can be explained by the low flow summer conditions monitored by TNRCC during the ecoregion study.

Average water temperatures ranged between 19.32 C and 21.72 C (range 2.4C) at all nine pools, and the median range was even smaller. The headwater Pool 1 had the lowest average temperature, which may be a result of its higher position in the watershed and the greater influence of ground water in the upper reaches of the creek. Low temperatures here may also reflect that this site was generally monitored in the morning, during the cooler part of the day. Average water temperatures throughout the watershed follow seasonal fluctuations in air temperature. The minimum temperature recorded was 9.04 C at Pool 4

Figure 3.3

Barton Creek Pools Study
Dissolved Oxygen Baseflow Concentrations



Source: COA /DUD Database 1990 - 1995

on February 1, 1991, and the maximum temperature recorded was 33.93 C at Pool 8 on August 2, 1993. TNRCC's average Central Texas Plateau ecoregion temperature of 28.1 is indicative of the summer season it was measured. Most temperatures measured in this study were well below TNRCC's surface water standard of 32.22 C for Barton Creek, Segment 1430 (Appendix E).

Differences in pH among the nine pools were minor, with means ranging between 7.63 at Pool 1 to 7.84 at Pool 5, and medians ranging between 7.65 and 7.83. The headwater site may be slightly lower in pH owing to the heavier ground water influence in the headwaters, but some differences in pH can also be attributed to the time of day a site is monitored. The pH values become more alkaline as increased photosynthesis removes carbon dioxide from the system and consequently less carbonic acid is formed. TNRCC's Central Texas Plateau ecoregion pH average of 7.8 was near the higher side of this study's average pH range. All pHs measured in this study were within TNRCC's surface water standard for Barton Creek, Segment 1430 (Appendix E).

3.2.4.3 Total Dissolved Solids and Conductivity

TDS and conductivity were measured by the same field probe and are closely related parameters; both are presented for documentation purposes (Figure 3.4). Conductivity averages ranged from 492 umhos/cm at Pool 5 to 602 umhos/cm at Pool 8. TDS averages ranged from 208 mg/L at Pool 5 to 268 mg/L at Pool 8. All TDS measurements in this study are in compliance with the TNRCC's surface water standard for Barton Creek of 500 mg/L, Segment 1430 (Appendix E). Pools 1, 7, 8, and 9 all have higher average conductivity, and Pools 1 and 8 have higher TDS than the other pools; however, only Pool 8 tested significantly different from all other pools with regard to conductivity and TDS. TNRCC's Central Texas Plateau Ecoregion conductivity average of 425 umhos/cm is lower than this study's average range. TNRCC's ecoregion conductivity is in the range of the minimum conductivities measured in this study. The 1988 BCPDR established a baseline geometric mean TDS of 236 mg/L at Loop 360 and Barton Creek, and this TDS falls in the middle of this study's average TDS range. Six other urban creeks monitored by Austin's Water

Watchdog Program reported median TDS values ranging between 300 and 420 mg/L, all substantially higher than TDS medians or means on Barton Creek resulting from this study.

TDS concentrations in the mainstem of Barton Creek can be impacted by nearby upstream spring discharges which are substantially higher in dissolved solids. Investigations by ERM of a perennial spring located just above Pool 8 measured the upstream/downstream impact to the mainstem surface waters. The investigation confirmed that Pool 8 was impacted by this spring (Appendix Photo 2B). An overall maximum TDS of 460 was recorded at Pool 8. This value was reported during a relatively low baseflow event (2.2 cfs on 8/8/94) and was very close to the TDS value measured at the spring discharge.

3.2.4.4 Turbidity

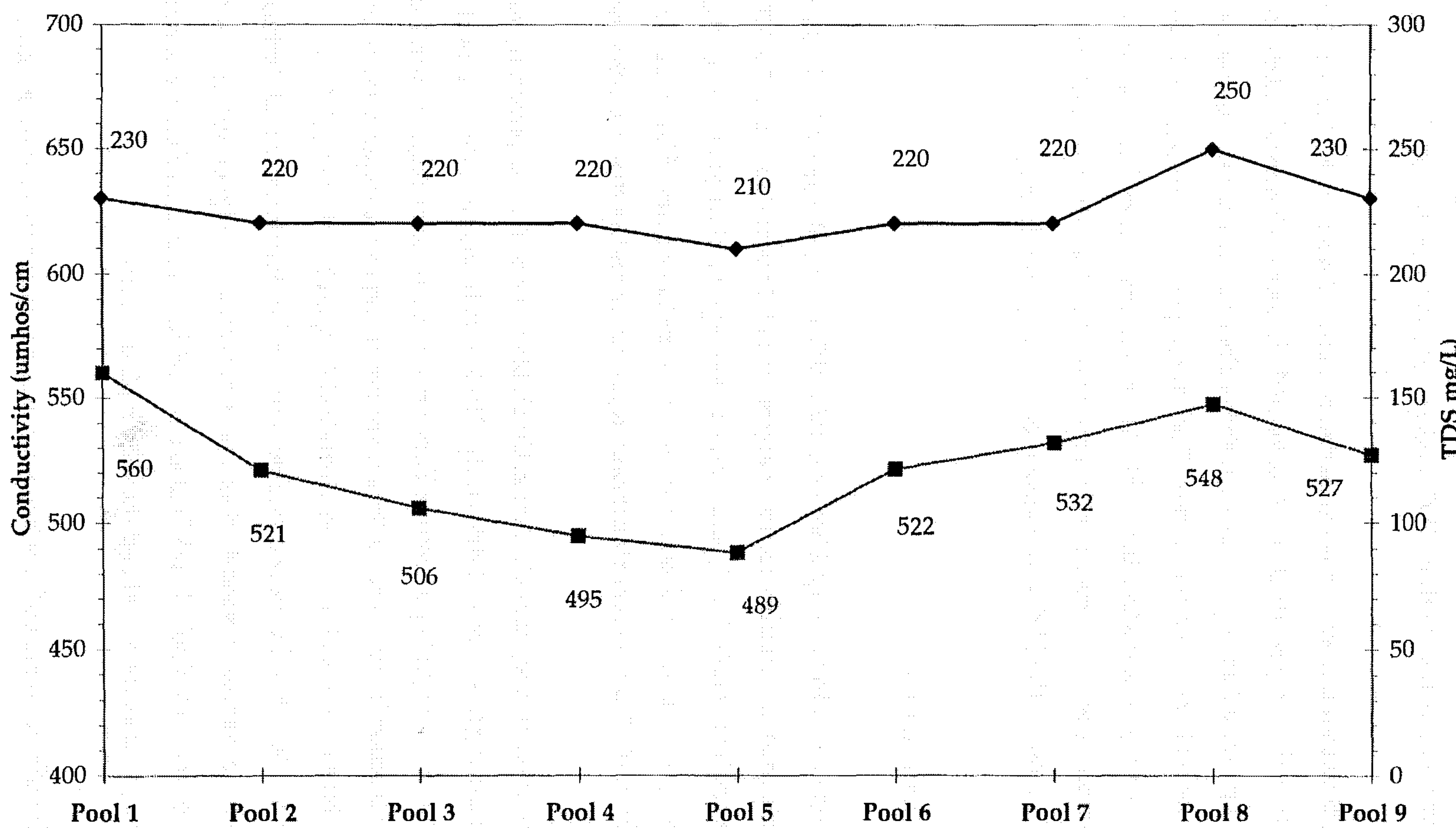
Average turbidity ranged between 0.84 NTUs at Pool 6 and 2.27 NTUs at Pools 7 and 9, while median turbidity ranged between 0.54 NTUs at Pool 4 and 1.7 NTUs at Pools 2 and 9 (Figure 3.5). Pools 2, 7, 8, and 9 all had average turbidities of greater than 1.5 NTUs, whereas Pools 1, 3, 4, 5, and 6 all had average turbidities of less than 1.5 NTUs; however, only Pools 7 and 9 were statistically higher in turbidity than the other pools.

Construction activities off Barton Creek Blvd. were in close proximity to Pool 7 just before and during the course of this study. Residents living near Pool 7 reported that a man-made impoundment just upstream of Pool 7 had become increasingly turbid since the construction began. The sediment accumulating in the impoundment was a fine silt which produced a milky cloud when disturbed (Appendix Photo 5C). Resuspension and transport of this fine silt is the most probable cause of the significantly high turbidity at Pool 7. Cattle ranching was also considered as a possible cause for higher turbidity at Pool 7; however, two other sites (Pools 1 and 3) also have cattle ranching in close proximity, and neither of these pools experienced significantly high turbidity.

Although the same milky white suspension was observed throughout the study at Pool 9 and in other natural impoundments immediately above Pool 9, no specific construction

Figure 3.4

Barton Creek Pools Study
Conductivity and TDS Baseflow Median Values



Source: COA /DUD Database 1990 - 1995

activities were observed or discovered in close proximity to these pools by ERM staff. One factor in common with the two study pools significantly higher in turbidity (Pools 7 and 9) was an impoundment directly above these pools. However, Pools 1, 2, and 8 also had water impounded above them and did not have significantly high turbidity. Impoundments potentially trap sediments, which can be resuspended and consequently elevate turbidities in pools directly below the impoundments. The conditions under which resuspension and transport of sediment occur are usually transitory, and may not have been represented consistently in the data set.

The maximum turbidity recorded during this study was 7.6 NTUs at Pool 7, and an overall minimum turbidity of 0.15 NTUs was recorded at Pool 6. Pool 7's high turbidity can be explained by a combination of construction activities and an upstream impoundment. Pool 6 was significantly lower in turbidity than all other pools and was characterized as a relatively small pool with a substrate composed principally of cobble and boulder, and a swift current with no impoundment upstream. Fine sediments were not easily trapped above or within Pool 6.

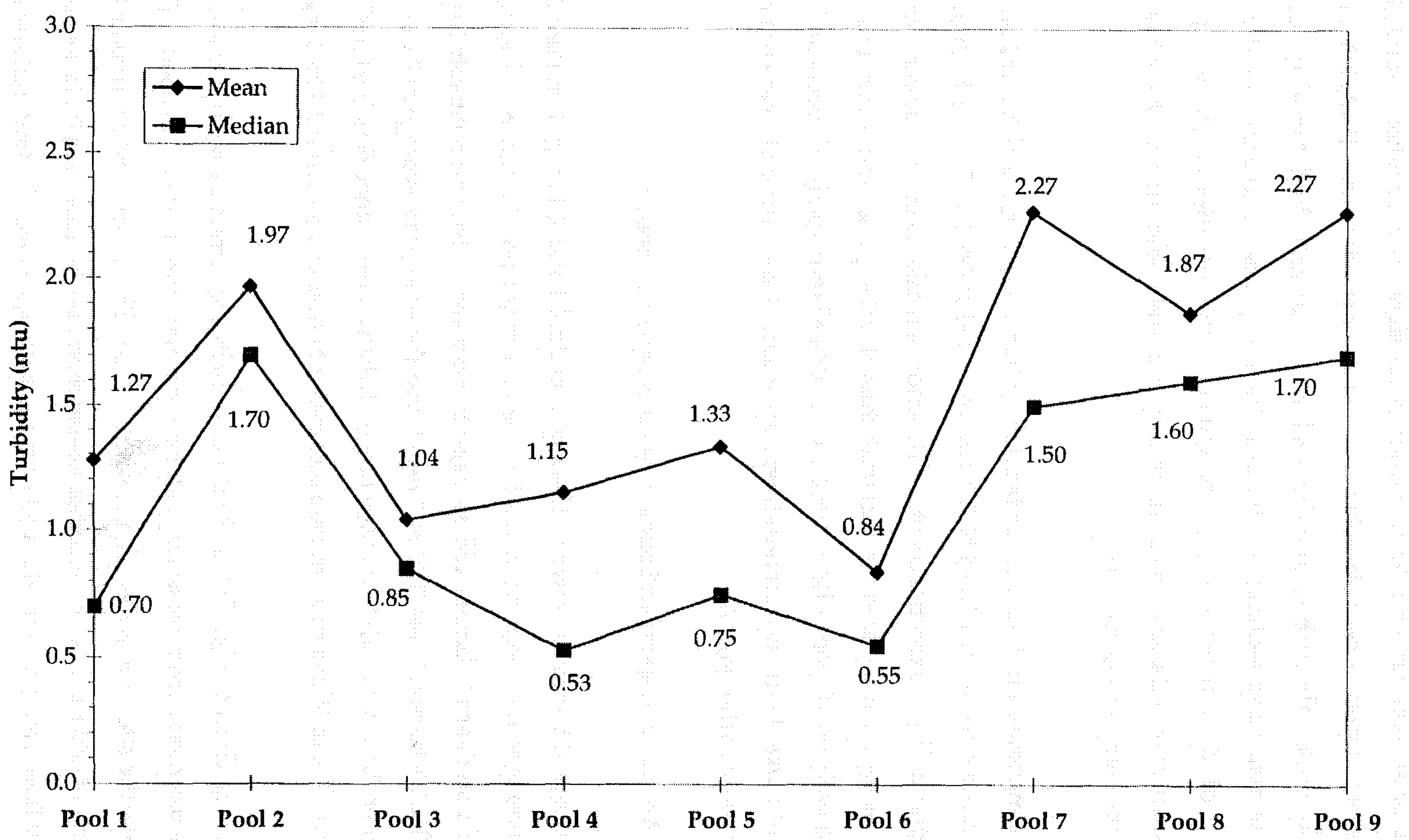
3.2.4.5 Total Suspended Solids, Volatile Suspended Solids

Average TSS ranged between 1.04 mg/L at Pool 4 and 4.11 mg/L at Pool 9. A comparison of averages and medians in TSS between the nine pools is shown in Figure 3.6. Only Pool 9 had a statistically higher TSS average; Pools 5 and 7 also had relatively high TSS averages. TNRCC's Barton Creek TSS of 5 mg/L and the ecoregion average of 9 mg/L are somewhat higher than this study's average range. Urban creeks, other than Barton Creek, monitored by the Water Watchdogs ranged somewhat higher in TSS, from 2.4 to 8 mg/L.

The significantly high TSS at Pool 9 is partially explained by resuspension and transport of fine sediments from those trapped from periodic runoff events in a natural impoundment above the site. Nevertheless, the source of this TSS is unresolved, similar to the anomalous high turbidity at Pool 9. Another explanation may be that Pool 9's large size and depth may slow flow velocity more than other sites, making it easier for finer sediment to be captured and resuspended in the pool itself. Pool 7's higher TSS concentration can be explained by

Figure 3.5

Barton Creek Pools Study
Turbidity Baseflow Values



Source: COA /DUD Database 1990 - 1995

the same factors as caused its high turbidity -- construction activities and resuspension of fines from an upstream impoundment. A milky white turbidity plume was observed by ERM staff entering Barton Creek above Pool 5 from the tributary of Little Barton Creek during one sampling event, and this site's maximum TSS of 8.3 mg/L was recorded on this date. The color and opacity of the plume was similar to construction site runoff; however, no specific site location could be identified as the source. In addition, no other natural phenomenon such as massive bank sloughing or cliff failure was evident in Barton Creek or major tributaries in the area.

VSS discerns the fraction of TSS which is organic as opposed to the mineral fraction, and the ratios of VSS to TSS are shown for each pool in Figure 3.7.

Generally, the pools with higher TSS values tended to have the lowest ratios of organic solids to total solids, indicating that mineral suspended solids are responsible for the higher TSS values at these sites. The lowest average ratio of VSS to TSS was 0.24 at Pool 9, while the highest was 0.68, occurring at Pool 4. The other seven pools have an average ratio of approximately one part VSS to three parts TSS or 0.33, and TNRCC's average ecoregion ratio was near the middle of this study's range at 0.44.

3.2.4.6 Bacteria

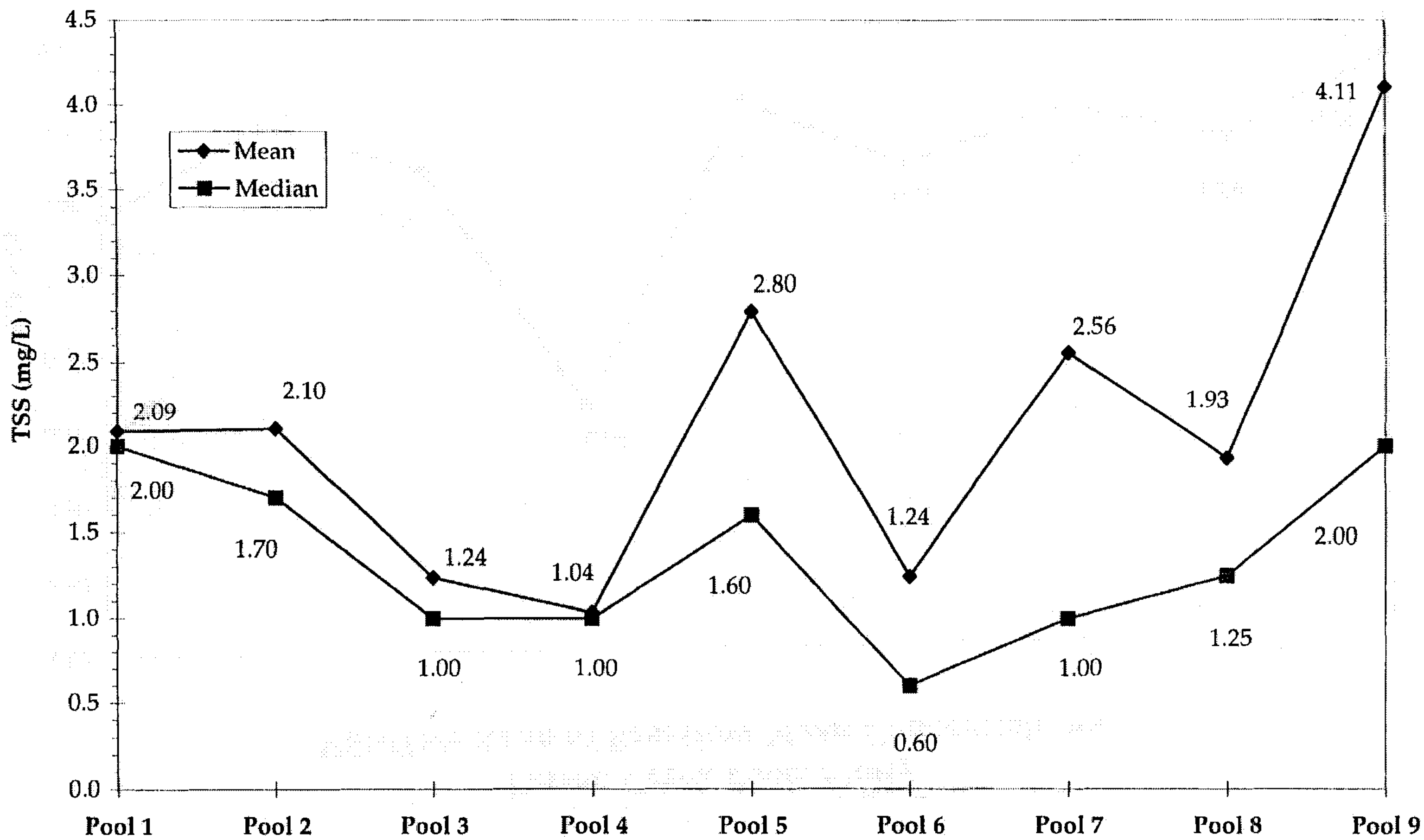
Fecal coliform averages were quite similar between sites with the exception of Pool 1 which averaged 238 colonies/100ml, more than twice any other site. Both medians and averages were statistically higher at Pool 1 as compared to the other eight pools (Figure 3.8). TNRCC measured 10 col./100ml at Barton Creek, and the ecoregion average was 55 col./100ml. The 1988 BCPDR recorded a geometric mean of 15 col./100ml at Loop 360 and Barton Creek. All of the nine pool sites in this study, except Pool 1, had average bacteria counts between 15 and 100 col./100ml.

Fecal coliform to fecal streptococci ratios were measured on two occasions at Pools 1, 2, 5, and 8. This method of differentiating the source of fecal contamination as human versus other warm blooded animals was accepted prior to the 1989 17th Edition of Standard Methods; however, because of streptococci false positives and die-off, the method is currently not considered reliable under all conditions. Nevertheless, this ratio is still being examined and has been found to be a useful tool in some environments (Baker and Hegarty, 1997); therefore, a limited number of fecal coliform to fecal streptococci ratios were examined. If the ratio is over 4.0, contamination is most likely domestic wastewater sources and feces of humans; however, ratios of 0.7 or less typically characterize contamination from other warm blooded animals, such as cattle or wildlife (Geldreich and Keener, 1969; Clausen, Green, and Litsky, 1977). An overall average FC/FS ratio of 0.59 indicates the source of contamination to be animal throughout the watershed; furthermore, no single ratio at any of the selected sites, including Pool 1, indicated the bacterial source to be human.

An active cattle ranching operation is located on properties immediately upstream of Pool 1, making this land use the most likely contributor of bacteria at Pool 1 (Appendix Photo 4B). No other source could be located in proximity to the sample site. Although fecal coliform counts were significantly higher at Pool 1 compared to other sites in this study, Pool 1's average (238 col./100ml) and median (85 col./100ml) concentrations were relatively low compared to the urbanized creeks in the Town Lake watershed (COA, 1994a). These urban creeks had a median fecal coliform concentration range of 700 to 5,040 col./100ml, and in comparison Barton Creek had a median concentration of 1435col./100ml at its confluence with Town Lake. This concentration at the mouth of Barton Creek may be related to the impact of animal feces; large numbers of ducks and geese reside at this monitoring site. TNRCC's contact recreation limit for fecal coliform is 400 col./100ml for ten or fewer samples (Appendix E) or a thirty day geometric mean of 200 col./100ml. Pool 1 is normally in compliance with the contact recreation criteria except immediately after a storm event which generates substantial runoff. In the recent 1996 TNRCC 305(b) report, Barton Creek was determined not to support the contact recreation use due to fecal coliform levels. This was based on quarterly sampling at eight sites by TNRCC. Given the variability of fecal coliform during runoff events and the myriad of other sources which could have impacted these sampling events, it is not surprising the City's baseflow data in pools above Barton Springs would indicate the criteria to be met. In addition, the distribution of sampling downstream of the pool could have influenced their conclusion.

Figure 3.6

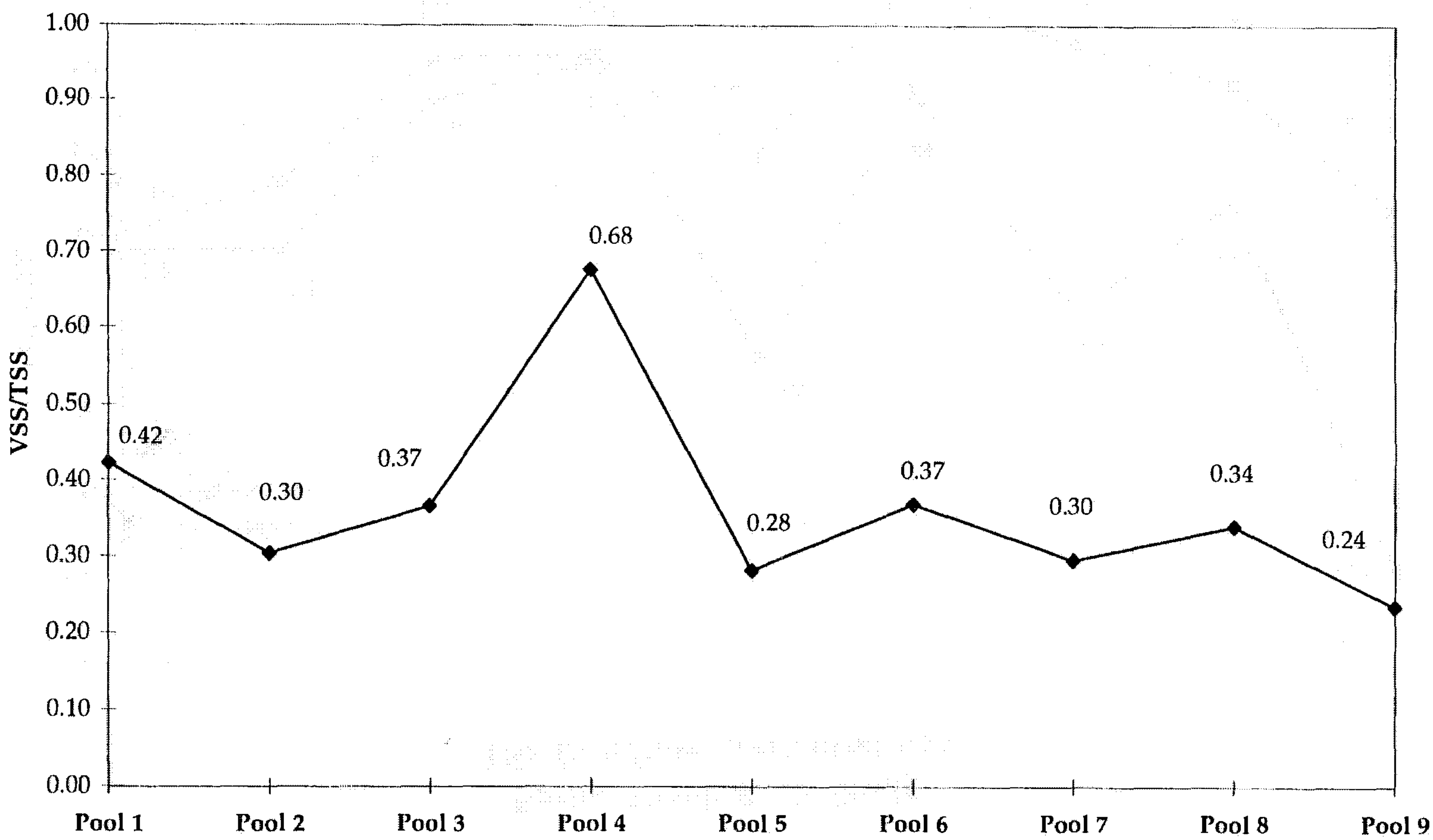
Barton Creek Pools Study
TSS Baseflow Concentrations



Source: COA /DUD Database 1990 - 1995

Figure 3.7

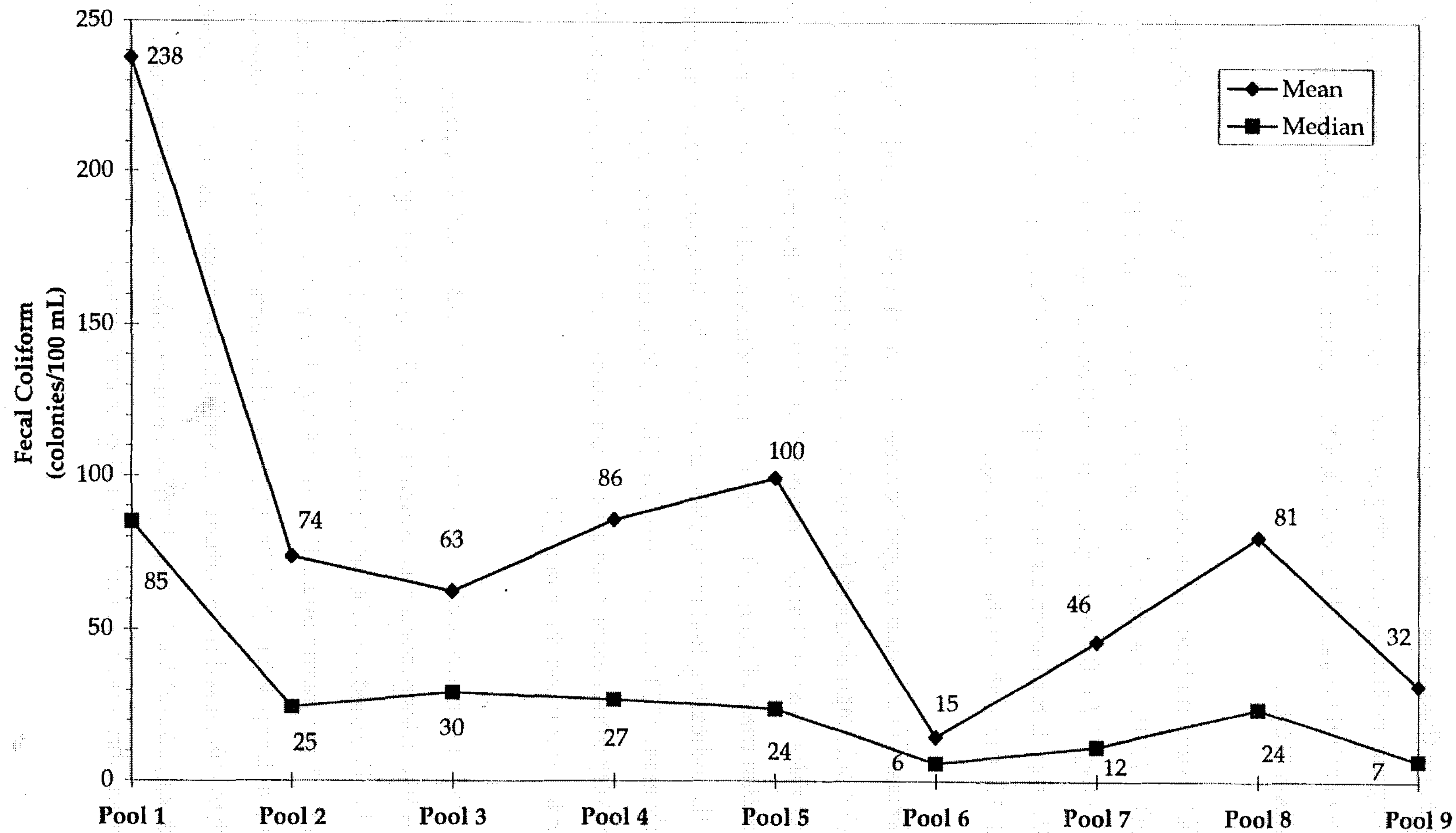
Barton Creek Pools Study
VSS/TSS Ratio of Baseflow Mean Concentrations



Source: COA /DUD Database 1990 - 1995

Figure 3.8

Barton Creek Pools Study
Fecal Coliform Baseflow Values



Source: COA /DUD Database 1990 - 1995

3.2.4.7 Oxygen Demand

Three methods were used to estimate a site's requirement for oxygen and evaluate the load of organic pollution, including organic debris, oils, and greases. These methods include Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC).

BODs were analyzed only once at two sites, Pools 5 and 8, and both sites had 0.5 mg/L BODs. TNRCC's ecoregion project reported 0.5 mg/L BOD at Barton Creek and an average of 1.3 mg/L for the ecoregion. The 1988 BCPDR established a baseline geometric BOD mean of 0.2 mg/L for Barton Creek at Loop 360. BOD appears to remain at or near detection limit (0.1-0.5) throughout the study area.

Average COD values ranged between 3.5 mg/L at Pool 5 and 7.7 mg/L at Pool 3, but no statistically significant differences were found between the nine sites. The single highest COD value was 18.3 mg/L, recorded at Pool 3, but the minimum for every site was the detection limit of 2.5 mg/L. The median values at all sites ranged between 2.5 mg/L and 5 mg/L, indicating that low CODs, at or near the detection limit, were normal throughout the study area. COD was not analyzed by TNRCC in their ecoregion project, but other relatively undeveloped streams in the Austin area (such as Bull Creek) also usually measure near the detection limit in COD.

TOC was measured only at two sites, Pools 5 and 8, and the difference observed between these two sites proved insignificant. Pool 5 averaged 6.18 mg/L and Pool 8 averaged 7.95 mg/L. The median TOC at Pool 5 was 2.75 mg/L, and the median TOC at Pool 8 was 3.59 mg/L. A geometric mean TOC of 2.8 mg/L was documented as the baseline for Barton Creek at Loop 360 in the 1988 BCPDR. This value is below the averages but near the medians observed in this study. Relatively high maximum TOCs detected at both Pool 5 (18.5 mg/L) and 8 (32.7 mg/L) may be responsible for the difference in TOC averages noted between this study and the BCPDR geometric mean.

3.2.4.8 Total Phosphorus and Orthophosphate as P

Although average total phosphorus varied somewhat, ranging between 0.02 mg/L and 0.05 mg/L, median total phosphorus values at all pools were nearly constant at or below the detection limit of 0.02 mg/L. Orthophosphate as P (ortho-P) averages also varied somewhat, ranging between 0.01 mg/L and 0.03 mg/L, but again the median ortho-P numbers were below the detection limit at all pools. Therefore, median total and ortho-P values indicated low phosphorus concentrations throughout the study area and no significant differences in phosphorus concentrations among sites. Also, no difference was observed between phosphorus levels at Barton Creek in this study and TNRCC's Ecoregion Project or the baseline established by the 1988 BCPDR. The Water Watchdog program reported median baseflow ortho-P concentrations between 0.05 mg/L (Harper's Branch) and 0.24 mg/L (Shoal Creek) in other urban creeks of the Town Lake watershed, and reported the lowest ortho-P median (0.03 mg/L) at Barton Creek.

3.2.4.9 Ammonia as Nitrogen

Ammonia nitrogen averages were virtually identical at all pools (0.03 mg/L); however, median ammonia values separated into two distinct groups: Pools 1 through 5 all had a median ammonia concentration of 0.02, and Pools 6 through 9 all had a median ammonia concentration of 0.03. Nevertheless, these median differences are not statistically significant. Ammonia is normally found in very low concentrations in most streams, because newly formed ammonia is oxidized rapidly into nitrites and nitrates. Similar NH_3 averages were documented in TNRCC's Ecoregion Project: 0.02 mg/L at Barton Creek and 0.03 mg/L throughout the ecoregion. The BCPDR also established an ammonia nitrogen geometric mean of 0.02 using 1978 - 1986 data. The other urban creeks of the Town Lake watershed, studied by the Water Watchdogs, had median ammonia nitrogen concentrations ranging from 0.07 mg/L (Blunn Creek) to 0.33 mg/L (East Bouldin Creek). The Watchdogs lowest median ammonia concentration (0.04 mg/L) was on Barton Creek.

3.2.4.10 Nitrate and Nitrite as Nitrogen

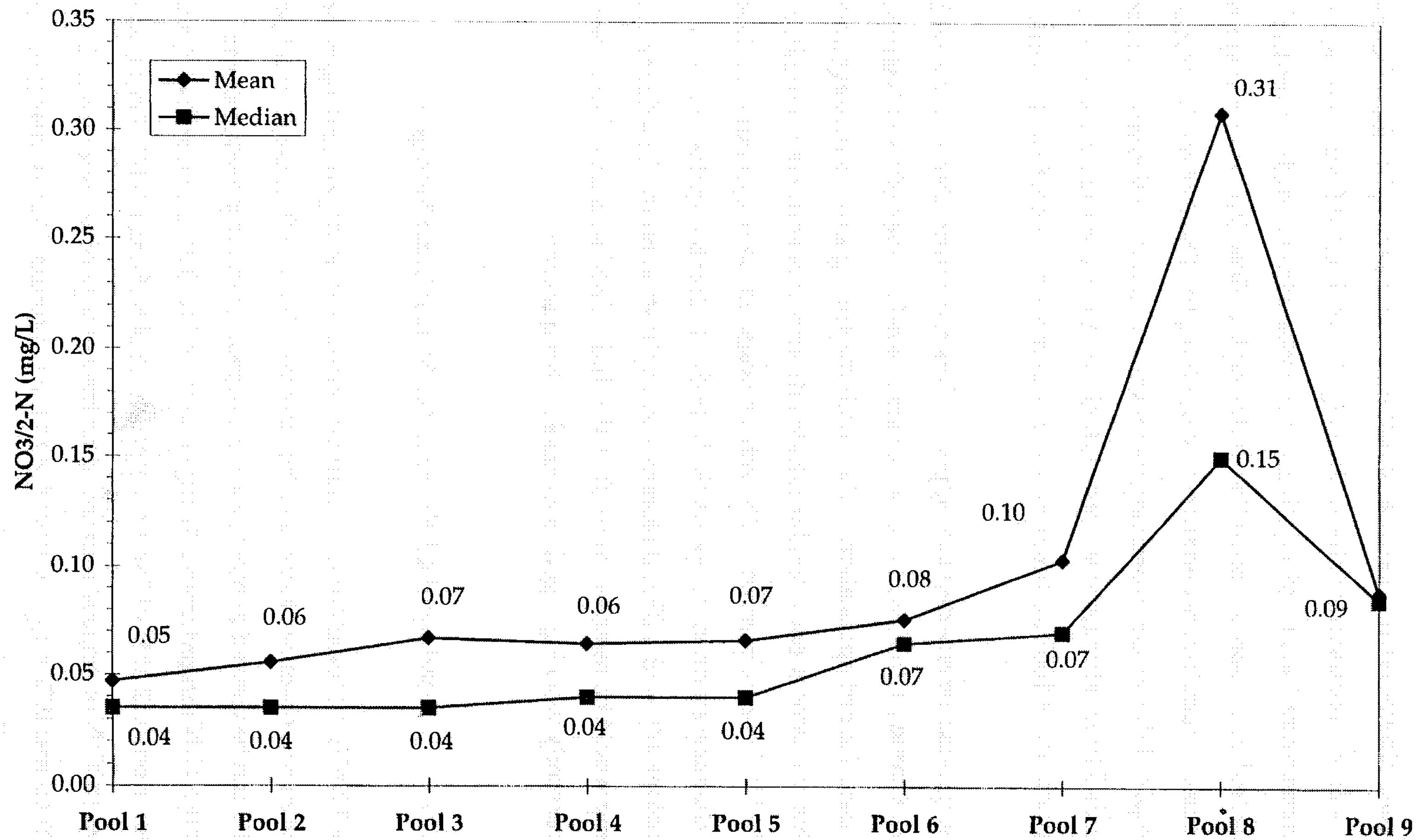
Nitrate+nitrite as nitrogen averages ranged considerably from 0.05 mg/L at Pool 1 to 0.31 mg/L at Pool 8. One high value of 2.48 mg/L at Pool 8 heavily influenced this site's average; however, Pool 8's median nitrate concentration of 0.15 mg/L was also substantially higher than the other pool's medians, which range from 0.04 to 0.09 mg/L. A somewhat lower nitrate+nitrite concentration was observed with both averages and medians in the upstream Pools 1 through 5 as compared to Pools 6 through 9, but the only significant nitrate concentration difference was observed at Pool 8 (Figure 3.9). The 1988 BCPDR established a baseline geometric mean nitrate concentration of 0.1 mg/L for Barton Creek at Loop 360. TNRCC reported a total nitrate+nitrite concentration of 0.02 mg/L on Barton Creek and 0.13 mg/L for the Central Texas Plateau ecoregion. Austin's Water Watchdog Program reported median nitrate nitrogen concentrations for seven urban creeks, including the mouth of Barton Creek, and they ranged from 0.1 to 1.1 mg/L. The median nitrate+nitrite nitrogen concentration at the mouth of Barton Creek, below Barton Springs, was reported to be 0.8 mg/L. Barton Springs was responsible for the higher nitrates measured at the mouth of Barton Creek, because Barton Springs averaged about 1.45 mg/L nitrate nitrogen (COA Ground Water Monitoring Program) and contributed significantly to the flow at the creek's mouth. Only one site in this study, Pool 8, had a higher average nitrate+nitrite concentration than the baseline of 0.1 mg/L established by the 1988 BCPDR.

Although determinations of nitrate and nitrite concentrations were normally made together, on one occasion (3/24/91) nitrate concentrations were analyzed separately from nitrite. These separate analyses showed, on average, nitrite made up, at most, 13 percent of the nitrate+nitrite mixture. This nitrite percentage was actually even lower, because the nitrite concentration was calculated using the detection limit, and nitrite was reported below the detection limit at every site on this date.

The spring above Pool 8 which impacted conductivity and TDS at this site also impacted nitrate+nitrite concentrations there (Appendix Photo 2B). Investigations by ERM staff have shown that nitrate concentrations in Barton Creek are about 0.1 mg/L higher below this

Figure 3.9

Barton Creek Pools Study
NO3/2-N Baseflow Concentrations



Source: COA /DUD Database 1990 - 1995

spring than above. This elevation in nitrates closely accounts for the difference in median nitrate+nitrite between Pool 8 (0.15 mg/L) and the other pools (about 0.05 mg/L). The average nitrate+nitrite at Pool 8 of 0.31 mg/L is much higher than the median of 0.15 mg/L because of one outlying value of 2.48 mg/L, obtained at Pool 8 during a low flow period. This concentration of 2.48 mg/L also coincides with the high concentration of nitrates measured at the spring above Pool 8 during low flow; however, the spring is known to fluctuate in nitrate concentration (see Section 2.0). The 2.48 mg/L seen at Pool 8 may be an example of the spring expressing its maximum impact at this site. This maximum nitrate recorded from laboratory analysis is believed to be accurate, because an unusually high conductivity of 1002 umhos/cm was also recorded at Pool 8 on the same date.

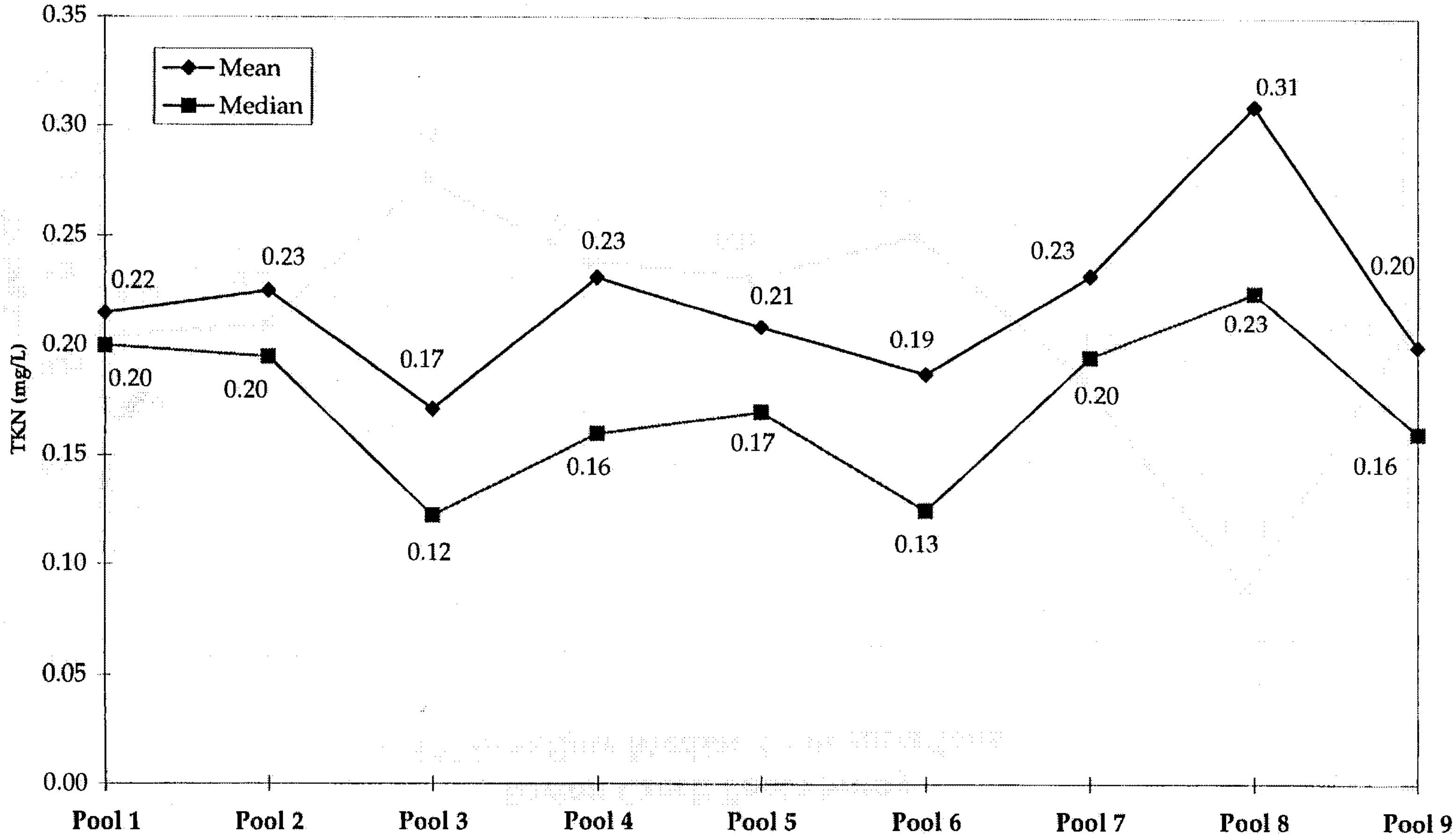
Underground terrace deposits appear to link the spring above Pool 8 with portions of Lost Creek Country Club's golf course, where treated sewage effluent is stored in a holding pond and used for turf application. When both the spring and the holding pond were monitored during the same month, similar nitrate nitrogen concentrations and nitrogen isotope ratios (N15/N14) were observed, both with a sewage effluent signature. Although some physical and chemical evidence supports the hypothesis that the spring above Pool 8 is linked hydrologically with effluent storage and application on the Lost Creek Golf Course, dye tracing would be required to confirm this link. ERM staff and Lost Creek Golf Course staff are currently working together to resolve this question.

3.2.4.11 Total Kjeldahl Nitrogen (TKN) and Total Nitrogen

Since TKN is a combination of ammonia nitrogen and organic nitrogen, and ammonia nitrogen was observed to be near the detection limit of 0.02 mg/L at all pools, the TKN results can be viewed in most cases as differences in the presence of organic nitrogen. Average TKN ranged from 0.17 mg/L at Pool 3 to 0.31 mg/L at Pool 8, and median TKN ranged from 0.12 at Pool 3 to 0.23 mg/L at Pool 8 (Figure 3.10). Pool 8 was significantly higher in TKN or organic nitrogen than the average of all other sites. The maximum TKN observed was 0.72 mg/L at Pool 8, and the minimum TKN or detection limit occurred at all pools except Pools 7 and 8. Although samples were not obtained for TKN analysis above

Figure 3.10

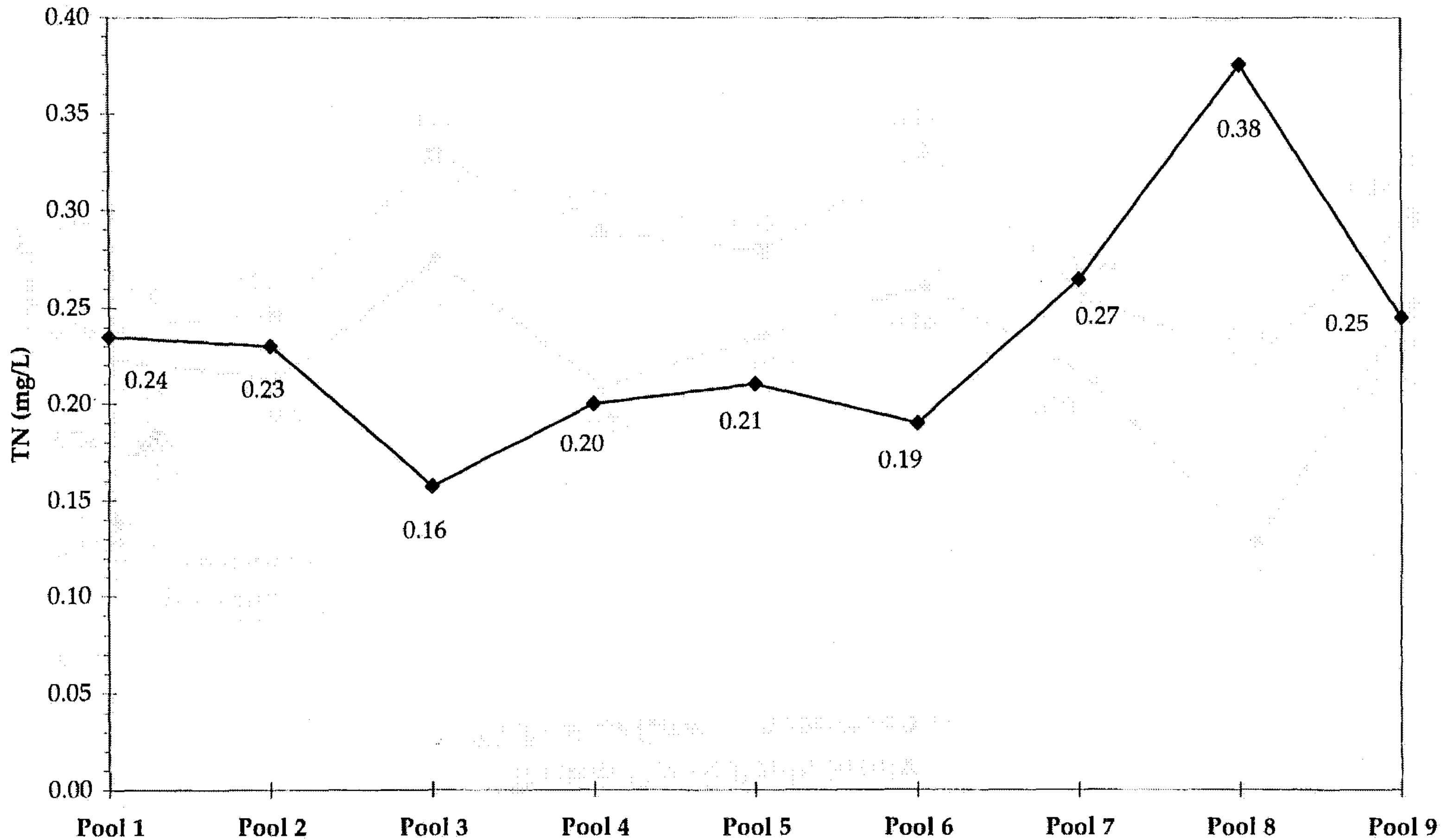
Barton Creek Pools Study
TKN Baseflow Concentrations



Source: COA /DUD Database 1990 - 1995

Figure 3.11

Barton Creek Pools Study
TN Baseflow Median Concentrations



Source: COA /DUD Database 1990 - 1995

and below the spring located upstream of Pool 8, TKN may be elevated at Pool 8 owing to impact from the same spring that elevates conductivity and nitrates.

All nitrogen species except ammonia were elevated at Pool 8; therefore, the total nitrogen at Pool 8 was also significantly higher than all other pools. Total nitrogen medians were calculated for each site by adding TKN and NO_{3+2} medians. TN medians ranged from 0.16 at Pool 3 to 0.38 at Pool 8. Figure 3.11 illustrates the median trends for all nitrogen species at the nine study pools.

3.2.4.12 Percent Algae Cover

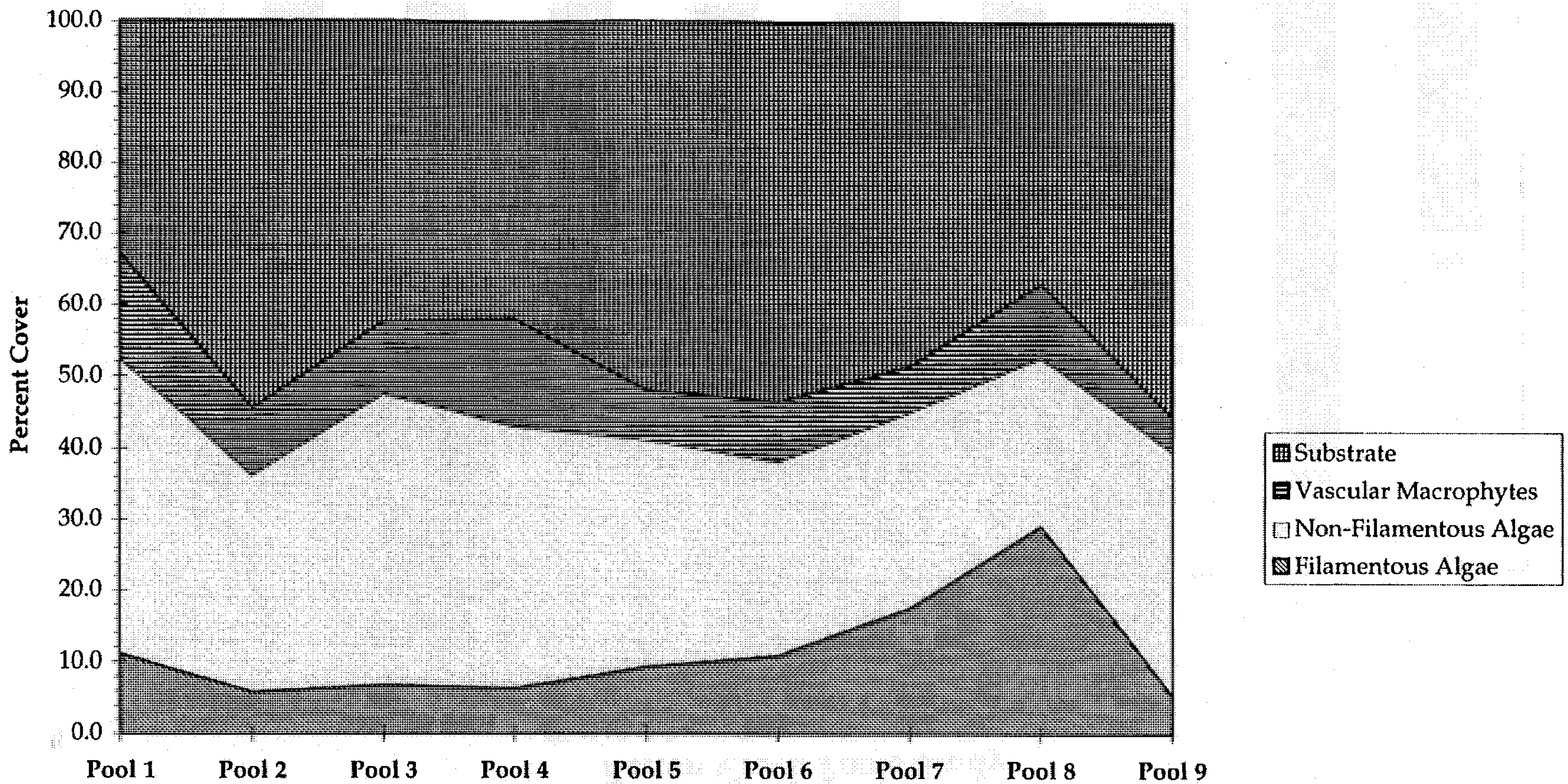
The waters of Barton Creek support a diverse algae community and natural distribution of the algae is dependent on flow, temperature, nutrients and canopy cover or available sunlight (Wetzel 1979, Hauerand Lambert 1996). Various species of green, blue-green and red algae, along with diatoms are common throughout Barton Creek. Carpet algae (a spongy amalgamation of sediment, diatoms, green, and blue-green algae species) is ubiquitous, growing on stream substrates throughout the watershed (Appendix Photo 6B). Algae provide an important source of biomass and cover for benthic macroinvertebrates and fish, but they may also reach nuisance levels due to eutrophication. In intermittent Central Texas streams, successional colonization reoccurs after periods of flooding and drought. The diatoms and blue-green algae colonize the scoured or recently re-watered substrate. In time, the green and red algae can establish themselves as major components of the stream biota. It is not uncommon to find strands of attached filamentous algae growing on substrates in lotic areas of the stream during periods of medium to high flow. As flow decreases in the mainstem during periods of extended low rainfall, pillows of unattached algae (*Spirogyra* "type") may appear in lentic regions and pools. Depending on rainfall and ambient conditions, pulses of increased nutrients may produce algae blooms of filamentous green algae, attached or unattached. Local *Spirogyra* "type" blooms can occur in any of the study pools when conditions are favorable (Appendix Photo 8B), but these blooms are usually short lived and do not tend to displace all other species of algae and aquatic macrophytes, as is the case with an attached *Cladorphora* bloom.

A diverse community structure of aquatic plants in Barton Creek includes submerged, floating, or emergent aquatic flora. Submerged plants include non-filamentous algae species with a vascular plant morphology such as the skunk-smelling *Chara* sp. or *Nitella* sp., which is referred to as poodle algae for its branches full of fuzzy spheres. Another submerged plant, the delicate vascular macrophyte *Utricularia* sp., bladderwort, illustrates aquatic adaptations by floating tiny yellow flowers to the surface for pollination. During favorable conditions, this tiny bladderwort can dominate the cover of a pool (Appendix Photo 6C). The reddish foliage of *Ludwigia* sp., water primrose, adds color to the submerged scene (Appendix Photo 11B), while the rich green foliage of *Potamogeton* sp., pond weed, sends primitive looking spiked flower stalks to the surface which are a favorite food of water fowl. Other submerged aquatics like najas grass, milfoil, or species of red and blue-green algae add to the variety of color and shapes visible in a pool with a diverse community structure. Several aquatic plants are commonly seen emerging from the shallows of Barton Creek like *Typha* sp. or cattail. Probably the most common emergent plant on Barton Creek is *Justicia* sp., water willow, which stabilizes sediments and bears attractive blue and white flowers. The ubiquitous *Eleocharis* sp., spikerush, stabilizes bottom sediments and muddy creek fringes alike. Mats of water-hyssop (*Bacopa* sp.) and the common frog fruit or *Phyla* sp. are common mudflat species. One of the most common plants stabilizing stream margins along Barton Creek is a lush clump sedge-grass called *Carex emoryii* whose native foliage looks like the exotic monkey grass, used to border landscapes in the city.

Figure 3.12 illustrates that total plant cover was greatest at Pools 1 and 8; however, the composition of the plant community was quite different between these two sites. Filamentous algae cover in Pool 8 replaced bare substrate, non-filamentous algae, and vascular macrophyte cover found in Pool 1 (Appendix Photo 6A). Although total algae cover was relatively uniform in all nine pools (Figure 3.13), Pool 8 was significantly higher than any of the other pools in filamentous algae cover (Figure 3.14). A dense *Cladophora* sp. population, reoccurred from 1990 through 1993, and accounted for much of the high average filamentous algae cover encountered in Pool 8. But other forms of filamentous algae cover have also been high at Pool 8 when *Cladophora* is reduced or absent. Pool 7 was

Figure 3.12

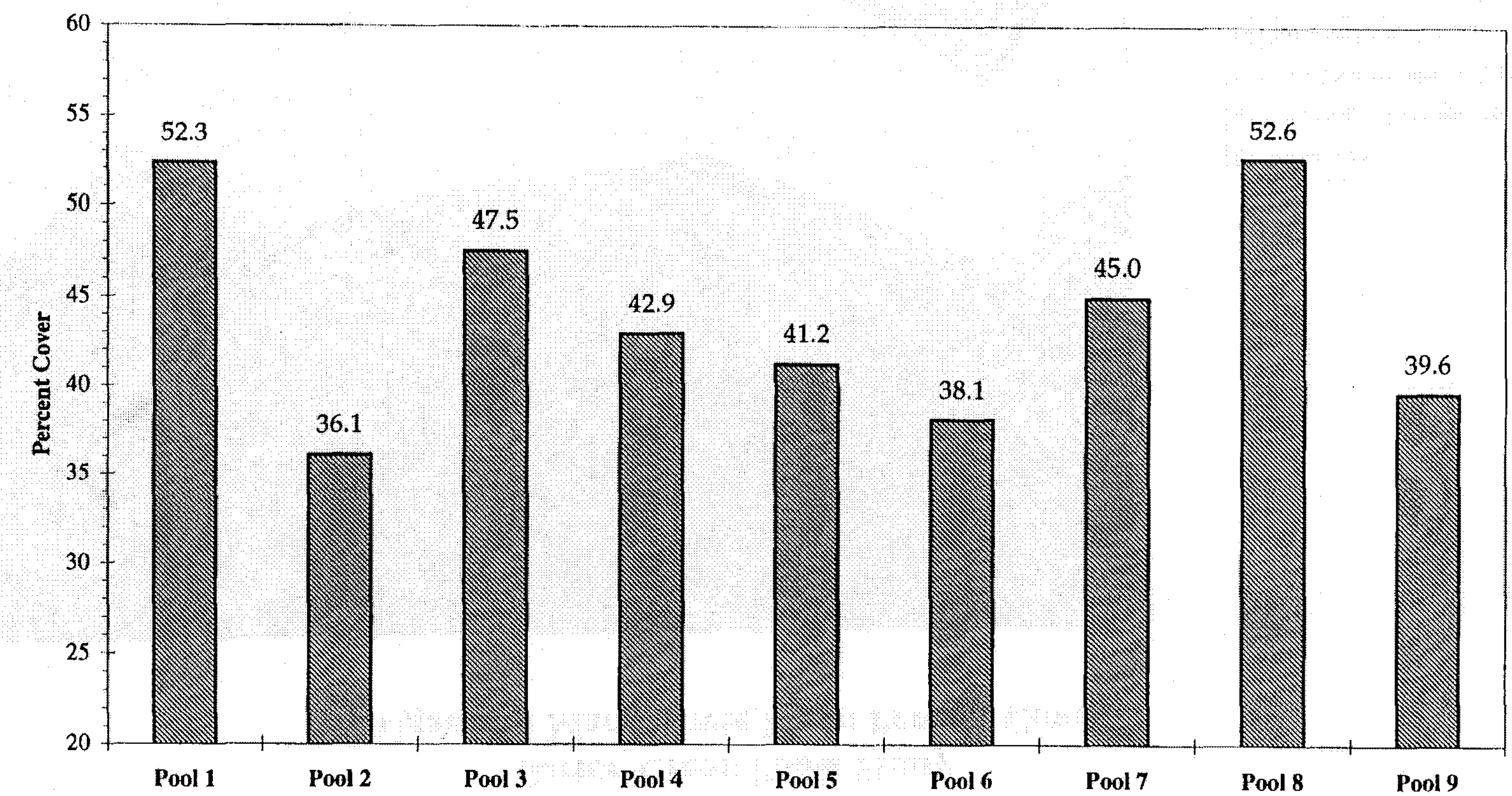
Barton Creek Pools Study
Algae and Macrophyte Mean Percent Cover



Source: COA / DUD Database 1990 - 1995

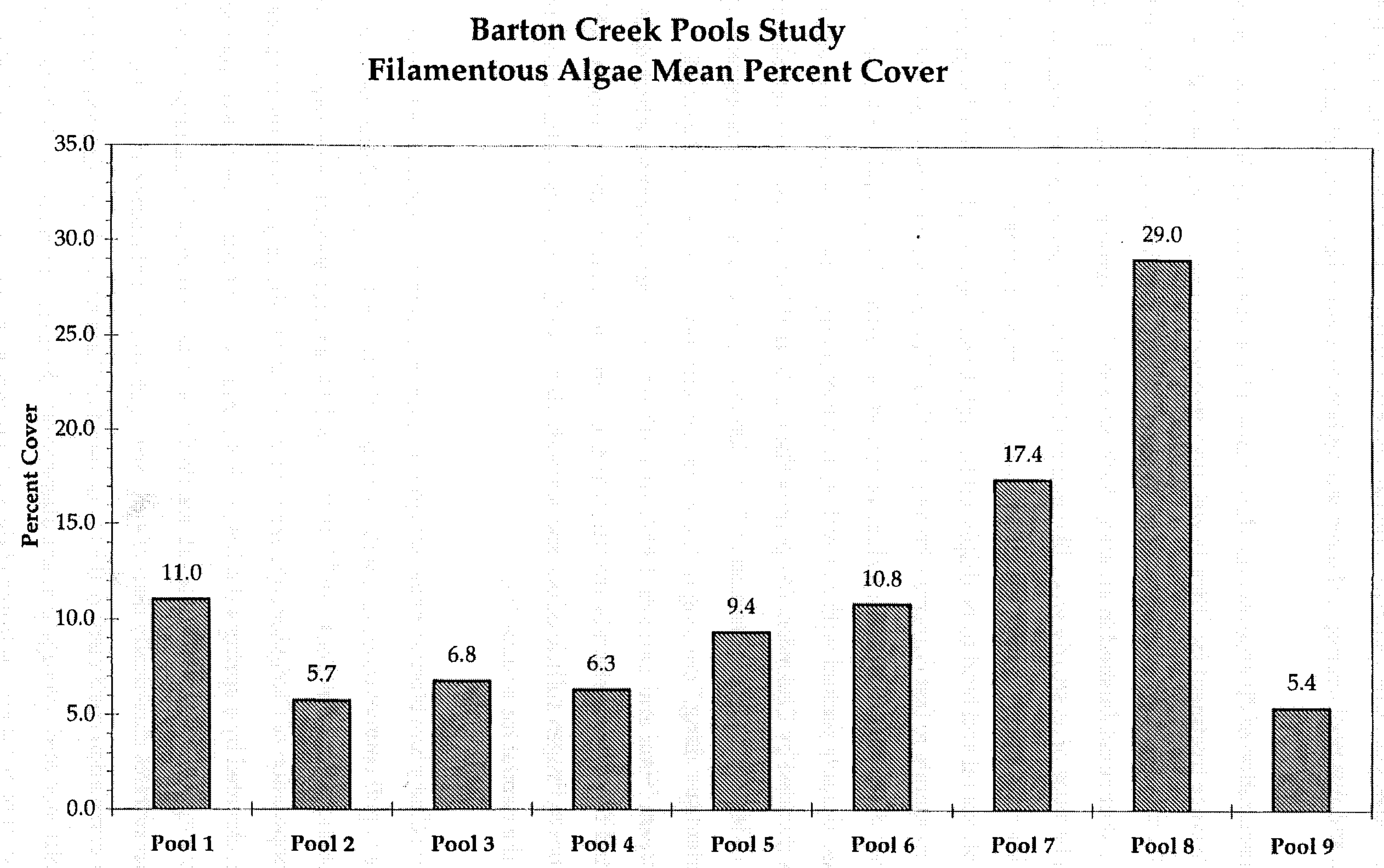
Figure 3.13

Barton Creek Pools Study
Total Algae Mean Percent Cover



Source: COA / DUD Database 1990 - 1995

Figure 3.14



Source: COA / DUD Database 1990 - 1995

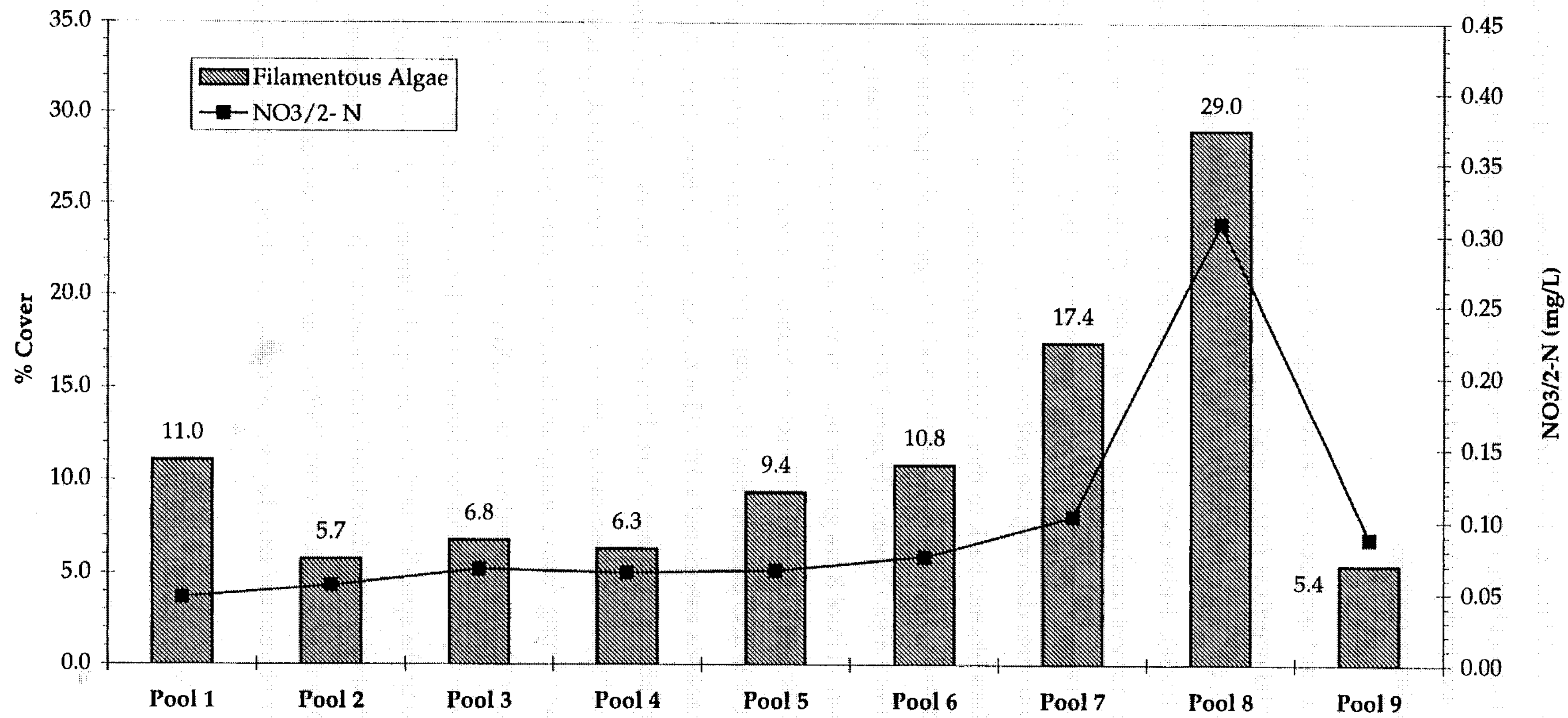
the only other pool to experience a dense cover of *Cladophora* on one occasion in 1993 (COA, 1993a), and this pool averaged the second highest average filamentous algae cover.

The deterioration of diverse aquatic flora, caused by a dominance of the *Cladophora* sp. below sewage treatment facilities, is well documented by other researchers (Wharfe, et al. 1983, Dodds 1991, Hynes 1970). Dense populations of *Cladophora* are uncommon in Barton Creek, but once established in an area, *Cladophora* tends to remain dominant for long periods of time because of its sturdy wool-like morphology which includes a tenacious holdfast or anchoring mechanism. Other filamentous algae species encountered in this study were more ephemeral and tend to be displaced by high flows more easily than *Cladophora* which prefers moderate to fast currents (Stevenson 1996). The biomass per unit area of *Cladophora* is heavier than other filamentous algae observed on Barton Creek, and bank-to-bank coverage, densely packed with as much as two meter long strands, is not unusual in stream reaches invaded by *Cladophora* (Appendix Photos 7A and 7B). Following such blooms the eventual death and decomposition of these dense mats of *Cladophora* in the creek may result in "nutrient spiralling," causing nutrient enrichment and increased algal growth downstream (Haur and Lamerti, 1996). In addition, the creek substrates which once supported these dense strands are afterwards covered with anaerobic sediments which contribute hydrogen sulfide odors and severely degrade the aesthetic value of the creek as well as the habitat for aquatic life.

Extensive *Cladophora* blooms have occurred in Barton Creek in areas where the predominant land use is golf courses irrigating with sewage effluent. A large population of *Cladophora* was first encountered at Pool 8 in November of 1990 and for several years the reoccurrence of this population of *Cladophora* appeared to be related to the higher nitrates measured at this site, elevated by a spring's discharge. Solid mats of *Cladophora* were also observed extending approximately 1.3 miles above Pool 8, and were originally thought to be caused by higher nitrates chronically discharging from golf course tributaries along this stretch. A positive correlation coefficient of 0.90 was found at the nine study pools between average nitrate nitrogen and average percent filamentous algae cover (Figure 3.15). However, in the spring of 1993, ERM staff witnessed the sudden establishment of another *Cladophora* bloom at and below Pool 7, extending the degraded stretch of *Cladophora* dominance

Figure 3.15

Barton Creek Report
Average Filamentous Algae and NO3/2-N
1990 - 1995



Source: COA / DUD Database 1990 - 1995

from 1.3 to 3.3 miles. This bloom provided information about the establishment of these dense monoculture *Cladophora* populations, indicating that the establishment of blooms may have more to do with acute spills and leaks rather than chronic discharges from golf course tributaries or springs.

Physical and temporal evidence suggest that the 1993 bloom at Pool 7 was triggered by the accidental overflow from a golf course waterfall recirculation pond, resulting in a discharge to Barton Creek of over 440,000 gallons of lake water mixed with small quantities of effluent (COA, 1993a). More recently, dense *Cladophora* populations were absent in Pools 7 and 8 during surveys conducted in 1994 and 1995. *Cladophora* blooms at Pools 7 and 8 were scoured away by heavy rains, and the relatively high nitrate discharges from the springs and tributaries draining the golf courses in the area have not been sufficient to bring the *Cladophora* blooms back to their former magnitude. It has been shown that in some systems algal growth is phosphorus limited and a surge of phosphorus results in *Cladophora* or other filamentous algae blooms (Hynes, 1970). The ambient nitrogen to phosphorus ratios in baseflows at Pool 8 are greater than 20 to 1, which is generally considered phosphorus limited (Borchardt, 1996). Therefore, because of the high phosphorus content in wastewater effluent, it is also possible that the 1990 - 1993 blooms were initiated by elevated phosphorus concentrations associated with effluent irrigation. Although the *Cladophora* has been virtually absent in recent years, Pool 8's higher nitrates have supported relatively high *Spirogyra* "type" filamentous algae cover in 1994 and 1995 (Appendix Photo 8A). Elevated nutrients coming from springs and tributaries into Barton Creek may serve to maintain a *Cladophora* bloom or greater cover of other filamentous algae, but may not be sufficient to initiate the types of *Cladophora* blooms which occurred from 1990-1993. The ambiguity concerning the specific nutrient causing the blooms is due to the influence of phosphorus at very low levels (near detection) and the availability of both nutrients in the wastewater events associated with blooms. Nitrates are sometimes used as a readily measurable indicator of nutrient enrichment regardless of which nutrient is limiting algae growth.

3.2.5 Conclusions

- Comparisons made among pools in this study illustrate some small but statistically significant spatial differences in water quality along Barton Creek's mainstem; however, various statistical analyses attempting to show temporal trends in water quality proved insignificant for the period of record of this study.

- From the pools studied in this project, it appears that one factor influencing baseflow water quality from the headwaters to the Recharge Zone is land use of the adjacent properties in the watershed between pools.

- Baseflow on Barton Creek gradually increased from upstream to downstream at an average rate of .63 cfs per mile, and flows ranging from 0.07 cfs to 390 cfs were observed during the course of this study as baseflow conditions (Section 3.2.2.3). Correlations between rates of baseflow and the concentration of constituents such as nitrates were found to be weak but inversely related.

- Dissolved Oxygen, water temperature, and pH were not found to be significantly different among the nine pool sites. With these parameters, small differences among pools may be related to differences in flow from upstream to downstream or differences in sampling times from morning to afternoon. In addition, no significant difference was found between sites for phosphorus, ammonia, TOC, BOD, and COD.

- Significantly high turbidity was measured at Pools 7 and 9, and Pool 9 is statistically higher in TSS than the other nine pools. The fine, milky white sediment associated with these pools may have been generated from nearby construction activity, but high turbidity and TSS at these sites may also be a function of sediment trapping in the deep, slow moving Pool 9 or in the upstream impoundment above Pool 7. In general, higher TSS values were caused by an increase in mineral sediment load rather than organic sediment load as observed through VSS to TSS ratios.

- Fecal coliform was significantly higher at Pool 1; however, bacteria counts were still very low there compared to urban creeks and normally within safe limits for recreational contact. Fecal coliform was probably of animal, not human, origin throughout the watershed, including Pool 1, where the source is most likely cattle.

- Pool 8 was significantly higher than all other sites in nitrates, TKN, TN, conductivity, and TDS. These elevations can be attributed to a spring which discharges just upstream of Pool 8. Some evidence suggests that the source of elevated nitrates at this spring may be an effluent holding pond on the Lost Creek Golf Course, but continued investigations, including dye tracing, would be necessary to be confident of this hypothesis.

- Pool 8 was significantly higher than all other sites in percent cover of filamentous green algae, principally due to reoccurring *Cladophora* sp. blooms there. Higher nitrates and conductivity correlated positively with higher filamentous algae at this site, but ERM staff have observed that *Cladophora* blooms can result from nutrient surges caused by accidental spills or mismanagement of irrigation effluent. The chronic, elevated nitrate discharges above Pool 8 may have maintained established *Cladophora* blooms rather than initiated them. To determine the specific triggering mechanisms for *Cladophora* blooms in Barton Creek additional data would be required.

In summary, surface water comparisons made among nine perennial pools over a five year period on the mainstem of Barton Creek indicated that the lower three study pools, all below Barton Creek Blvd., were each impacted by either significantly higher nitrates, TDS, TSS, or turbidity. The other six pools upstream of Barton Creek Blvd. showed no significant degradation with the exception of significantly higher fecal coliform at the most upstream headwater pool. It is important to note that impacts to each of the lower three pools were localized and not ubiquitous along this lower reach of the creek. Water quality impacts seen at one study pool will diminish before reaching the next study pool, only to be replaced by other impacts related to local land use or construction activities.

Baseflow water quality above Barton Creek Blvd. was fairly homogeneous, and the water chemistry along this reach of the mainstem has not deteriorated substantially since the 1988 *Barton Creek Policy Definition Report* was written. The baseflow water chemistry throughout the study area is still excellent compared to other streams contributing to Town Lake studied by Austin's Water Watchdog Program and to least-disturbed streams studied by TNRCC in the Central Texas Plateau ecoregion. Evidently, enough relatively pristine waters still flow from Barton Creek's rural and undeveloped areas to dilute impacted discharges from developed tributaries and springs located further down the watershed. The conclusions of this study are consistent with national data documenting limited impacts detectable in the current impervious cover range of the Barton Creek Watershed (Schueler, 1995).

Further development in the Barton Creek Watershed that does not provide adequate baseflow protection and impervious cover limits will most likely be associated with the following impacts during baseflow periods: (1) diminished water clarity in impounded and slower-moving waters, resulting from construction-related runoff; (2) replacement of a diverse aquatic flora with a monoculture of *Cladophora* algae below lands where there is potential for mismanagement of treated sewage effluent used for irrigation; (3) maintenance of heavier filamentous algae cover in the mainstem owing to nutrient-enriched waters draining to Barton Creek from developed tributaries and springs.

3.2.6 Recommendations For Future Monitoring

The City's surface water monitoring program has established an excellent temporal and spatial data base along the mainstem of Barton Creek since 1990, examining trends in water chemistry and vegetative cover in perennial pools from the headwaters to the Recharge Zone. However, monitoring of these pools must continue to determine long term trends, track the health of the creek, and to identify specific causes for algae blooms. Therefore, it is recommended that the City continue quarterly monitoring of eight of the nine mainstem pools for water chemistry and percent algae cover. Pool 2 can be dropped, because the pool is gradually receding due to natural changes in creek morphology; it may not be a perennial pool in the near future, and other upstream pools are adequate to provide rural water quality data. An additional water chemistry site is recommended immediately above Barton Creek Blvd. to track water quality before entering the lower third of the study area, where most impacts have been detected.

In order to determine short term impacts from storm events or other forms of pulse loading, it is recommended that three *in situ* data loggers be deployed along the mainstem of Barton Creek: in Pool 3, above Barton Creek Blvd., and in Pool 8 or 9. This will provide continuous water quality information at a rural site, a site immediately upstream of the impacted reach of the study area, and a site near the downstream end of the study area. It would also be beneficial to conduct 24-hour dissolved oxygen monitoring in each of the regularly monitored pools, at least once per year during summertime, low flow conditions.

Additional chemical assessments are recommended at selected pools on a regular basis. Sediments should be analyzed at all pools on a quarterly basis in ERM's laboratory for total petroleum hydrocarbons using a cost effective immunoassay technique. A full suite of toxic sediment constituents, including pesticides, should be analyzed every third year in one select pool located in each third of the study reach.

Additional bioassessments are recommended. Benthic macroinvertebrates should be monitored in each of the regularly monitored study pools at least once a year and quarterly at a select pool in each third of the study reach. City collaboration with TNRCC's Surface Water Quality Monitoring Team has been suggested for this task. Other methods of quantifying periphyton growth should be employed at all study pools as indicators of water quality, including determinations of diatom community structure and biomass of periphyton collected from artificial and natural substrates (Hynes 1970, Wetzel 1979, Haur and Lamberti 1996). Additional factors affecting the growth of algae such as stream velocity, solar incidence, substrate characteristics, and depth should be monitored to correlate with percent cover of filamentous algae growth to further investigate the factors affecting algal growth (Weitzel 1979, Hauer and Lamberti 1996).

It is recommended that an investigation using ground water tracers be made to confirm the source of higher nitrogen and conductivity values at Pool 8. Cooperative dialog is currently taking place between Lost Creek MUD and ERM staff to initiate this investigation. If it is determined that any effluent holding ponds on the Lost Creek Country Club golf course are leaking, remedial action should be negotiated. Remediation may be timely, in that Lost Creek MUD may be enlarging their holding capacity in the near future; therefore, effective liners could be retrofitted in the process.

Data collected by Austin Community College students and other citizens involved in the City's Water Watchdog Program have been used in this report and in the City's Town Lake Study Report to compare and contrast water quality in many of our urban streams, including Barton Creek. It is recommended that the City's environmental staff coordinate monthly Citizen Monitoring assessments at mouths of all streams in Austin for comparison purposes. A regional approach should be taken to involve not only the Water Watchdog Program, but also the City funded Opportunities For Youth Program, Travis County Streamwatch Program, TNRCC Texas Watch Program, and the LCRA Colorado Riverwatch Program. The efforts of these volunteer groups will then be focused on a common goal: production of an annual index of chemical water quality for public information. This interlocal participation could then more effectively promote and coordinate creek and lake cleanups, creek restoration and stabilization, storm drain marking, distribution of educational materials throughout each watershed, trail building, and other community involvement projects. LCRA has also expressed support for this recommendation in their review of an earlier draft of this document.

3.3 BARTON CREEK CANYONS STUDY

3.3.1 Preface

Barton Creek lies within the Balcones Canyonlands subregion of the Edwards Plateau biotic region (LBJ School of Public Affairs, 1978). The Balcones Canyonlands are formed on the Balcones Escarpment, which is highly eroded and dissected as compared to the higher, nearly level, central part of the Edwards Plateau. It is this dissected landscape that gives the Barton Creek Watershed and other areas west of Austin their unique morphology and character. Numerous tributaries empty their contributing waters into the mainstem of

Barton Creek, and as Barton's watershed develops, each canyon or tributary's land use may be mirrored by its water quality. The Barton Creek Canyons Study, like the Barton Creek Pools Study, is part of an effort to assess and track the water quality in the Barton Creek Watershed as authorized by the Austin City Council.

In November of 1990, the City of Austin's Environmental Resources Management Division, began a study of the baseflow water quality and algae cover at nine sites in the mainstem of Barton Creek from the headwaters to the Edwards Aquifer Recharge Zone. During the course of this study, annual investigations were made in which an entire stretch of the creek from Highway 71 to Lost Creek Blvd. was surveyed by canoe, and individual tributaries contributing to Barton Creek were sampled for a comprehensive longitudinal water quality assessment. Although baseflow water quality remained fairly homogeneous from upstream to downstream in the mainstem of Barton Creek, substantial differences were observed between contributing tributaries, and these differences appeared to be related to land use. During a survey of Barton Creek in the spring of 1993, following the appearance of a new *Cladophora* sp. algae bloom in the mainstem, ERM staff observed several tributaries with elevated nutrient regimes, and all were associated with watersheds containing either golf course or high density residential development (COA, 1993a). Although mismanagement of domestic wastewater effluent used for irrigation may have initiated the 1993 *Cladophora* bloom in the mainstem of Barton Creek, high nutrient concentrations discharging from developed tributaries may have contributed to the maintenance of nuisance levels of algae over longer periods of time, and cumulative impacts of elevated nutrient concentrations may be enough to both initiate and maintain undesirable levels of filamentous algae in some areas of Barton Creek in the future.

Based on this preliminary tributary data, ERM designed a monitoring study to determine if significant water quality differences exist between tributaries draining three major categories of land use: (1) golf courses, (2) high density residential developments, and (3) rural areas representing ranching and low density residential development. This study was initiated in response to concerns expressed at Council and the Environmental Board concerning upland development in the Barton Creek Watershed.

Water quality in canyon tributaries with a known dominant land use was compared as an indicator of each land use's relative impact on Barton Creek. Furthermore, baseline water quality data was obtained from rural tributaries which are currently developing or may develop in the near future under the City of Austin's water quality ordinances. Several strategies were implemented in this study design to compare water quality between the three land uses:

(1) The baseflow water quality was sampled in as many different Barton Creek tributaries as possible to obtain baseline data and compare water quality by characterizing the land use in each canyon as one of the three major land use categories.
(2) Three representative tributaries were selected, one from each land use category, to be sampled for baseflow water quality on the same day, once each month.
(3) Water quality was sampled during several storm events from the three representative tributaries at precisely the same time during the storm.
(4) Using data from all Barton Creek tributaries, the three main land use categories were subdivided into watersheds using alternative wastewater disposal strategies for water quality comparisons.
(5) The water quality differences in two residential canyons were compared with different sized buffer zones surrounding the stream.

3.3.2 Methods

3.3.2.1 Site Selection

All together, 38 sites on tributaries located in the Barton Creek Watershed were sampled in conjunction with various Barton Creek monitoring programs (Plate 3, Appendix F). A data base was maintained for all tributaries to Barton Creek and each stream was characterized as residential, golf, or rural. Three representative tributaries of these land uses were selected and monitored regularly, on a monthly basis. Although the extrapolation of statistical inferences from "representative" sites suggests pseudo-replication (Hurlbert, 1984), obtaining replicates was not possible early in the study with available resources.

In a separate analysis of the same data set, the 38 sites were grouped into the following alternative sewage treatment categories for analysis: golf courses using treated wastewater effluent for irrigation (GEI), residential areas spraying treated wastewater effluent on native grasses (REI), residential areas on septic systems (RS), residential areas on a central sewage system (RC), or rural areas that are ranched or largely undeveloped (R). The groupings were made on the basis of watershed reconnaissance and predominant land use impacts observed. Additional analysis of watershed characteristics is planned using recent aerial surveys.

The three representative tributaries for golf, residential, and rural land use were selected based on three criteria: (1) the two developed subwatersheds were fully built out, one as solely a residential neighborhood density, the other solely a golf course; the rural watershed was either vacant, ranched, or with a very low density of residences (five to ten percent total impervious cover); (2) all three subwatersheds had perennial baseflow, in order to collect samples monthly; (3) all three subwatersheds were in close proximity to each other so that storm events impacted all tributaries with the same amount of rainfall. An ideal regional center for the three representative canyons was found at the Lost Creek Blvd. bridge over Barton Creek, because the City of Austin operates a Flood Early Warning System rain gauge there; precipitation quantities were obtained for the precise time of a storm water collection. An effort was made to select watersheds of roughly the same size, but the absence of perennial baseflow eliminated many candidates from consideration. Three perennial flowing tributaries were found within one mile of the Lost Creek FEWS station. The representatives for residential and golf course land use were less than 100 acres in size (72.1 and 22.9 acres respectively), but a larger watershed area was necessary to obtain perennial flow in a rural setting (1,904.8 acres). The residential canyon was a fully developed watershed in the Lost Creek Subdivision (Ringtail Ridge Canyon or RRC); the golf course canyon was located on the Crenshaw Golf Course of Barton Creek Properties (Crenshaw Tributary or CRT1); and the rural canyon was the upper portion of Short Spring Branch tributary, upstream of the Lost Creek Golf Course and Barton Creek Estates residential subdivision (Short Springs Branch at Estates or SSBE), (see Table 3.5, acreage and impervious cover information). Water was collected at the mouth of RRC and CRT1 or the confluence of these tributaries with the Barton Creek mainstem, and water from SSBE was collected several hundred feet upstream of Lost Creek Blvd. Land use and site abbreviations are provided in Table 3.6 along with wastewater strategy classification and buffer size.

One additional residential tributary within the Lost Creek Subdivision, discharging just downstream of RRC, was sampled monthly and during storm events along with the other three representative tributaries. This tributary, LCR, was not selected as a principal representative of residential land use because it did not have perennial flow. However, it was sampled, when flowing, to compare water quality between two adjacent residential watersheds with different sized undeveloped buffer zones surrounding the stream. LCR canyon is part of the Barton Creek greenbelt system and has an average of 760 feet of undeveloped buffer on either side of the stream up to the headwaters. Site RRC, the representative residential canyon, has a much smaller buffer, averaging approximately 228 feet, and some landscaped yards come immediately adjacent to the stream bank. The average buffer for both canyons is relatively high, because the Barton Creek greenbelt is calculated into the average.

3.3.2.2 Sampling Protocol

Surface water samples were collected by ERM staff from the mouth of each stream or at an upstream site which represented the drainage of a particular land use. Standard collection methods were employed to prevent contamination and insure preservation of samples; all analyses with the exception of pH were conducted in accordance with the 19th Edition of *Standard Methods For Examination of Water and Wastewater* (American Health Institute, 1995). Some pH measurements were not made in the field as is recommended; samples taken at various locations by different teams were brought back to the lab for analysis by a single instrument. Parameters measured in the laboratory include the following: nitrate-nitrogen, ammonia nitrogen, ortho phosphorus, fecal coliform, turbidity, total suspended solids, pH, and total dissolved solids.

Table 3.5
Acres of Various Land Uses in the Barton Creek Canyon Sites

	Vacant	Parks & Golf	Single Family	Office	Utilities	Total Acres	Total Impervious Cover	Percent Impervious Cover
CRT	2.12	20.84				22.96	1.15	5.00
LCR	106.82		72.30	6.61	0.58	186.32	31.14	16.72
SSBE	1831.10		73.71			1904.81	113.67	5.97
RRC	18.39		53.73			72.12	17.04	23.62

Source: City of Austin, Drainage Utility Department GIS Database, 1997

Table 3.6 Land Use and Site Abbreviations

Site Abbreviations	Land Use	Wastewater Strategy	Buffer Size
GEI	Golf	Effluent Irrigated	NA
REI	Residential	Effluent Irrigated	NA
RS	Residential	Septic Systems	NA
RC	Residential	Central System	NA
R	Rural	None/Some Septic	NA
CRT1	Golf Representative	Effluent Irrigated	NA
SSBE	Rural Representative	None/Some Septic	NA
RRC	Residential Representative	Central System	228 ft. Smaller
LCR	Residential	Central System	760 ft. Larger

Other information such as flow, water temperature, last rainfall, and existing weather conditions were measured or noted in the field. Flow was measured with a Marsh McBirney Model 2000 velocity meter using methods recommended by TNRCC's 1993 *Water Quality Monitoring Procedures Manual*.

Baseflow conditions were defined as follows: at least 12 hours following measurable precipitation of less than 0.5", at least 24 hours following a rainfall of between 0.5" and 1.0", and at least 48 hours following a rainfall of greater than 1.0". Baseflow water quality samples and flow measurements were taken in the three representative streams concurrently, once each month; and intermittently collected baseflow data from all 38 subwatersheds were also used in a comparative analysis of various land uses. Stormflow samples were grabbed at the three representative sites simultaneously when precipitation measured between 0.5" and 1.0" at the Lost Creek FEWS station. Water quality comparisons were made between sites, because the samples were taken in the same portion of the rainfall event. Although this was only an approximate method of first flush sampling, more rigorous monitoring over the hydrograph would have required a continuous flow monitoring station at these locations. No attempt was made to match sample timing with occurrence of the hydrograph peak; however, this is addressed in recommendations for future monitoring.

For a discussion of the quality control and analyses for statistical significance used in the Canyon Study see the Barton Creek Pools Study text, Sections 3.2.2.5 and 3.2.2.6.

3.3.3 Results

ERM staff began assessing water quality in Barton Creek tributaries as early as April of 1992; however, a monitoring work plan was written and contemporaneous sampling began in April of 1994 to compare the three representative canyons. Using the data obtained at 38 sites, representing approximately 200 random baseflow observations, means, medians, maximums, and minimums have been determined for three principal categories of land use -- golf, residential, and rural (Table 3.7). These statistics have also been calculated for the three principal land use categories using data obtained at RRC, CRT1, and SSBE, describing baseflow, storm events, and post storm conditions (Table 3.8). Furthermore, water quality statistics in two residential canyons, RRC and LCR, with different sized buffer zones are also compared (Table 3.9). Data are also organized to compare water quality between rural (undeveloped) sites with canyons characterized by alternative uses of waste water effluent: golf sites using treated effluent irrigation, residential sites using treated effluent irrigation, septic systems, and central wastewater systems (Table 3.10). An overview of statistically significant results for each of these comparison schemes is shown in Table 3.11 (Appendix H). Nonparametric (Kruskal-Wallis and Brown-Mood Median Analysis) tests show whether parameters are statistically different anywhere within a given analysis grouping; whereas multiple comparison (Contrast) tests show where the significance is when comparing any two groups. Using alternate methods of handling non-detect data the results of non-parametric comparisons would change for isolated contrast tests on TSS and NH_3-N.

Additional comparisons would change depending upon assumption of rank value for non-detects in isolated tests on turbidity and orthophosphate. The additional tests do not

Table 3.7

Barton Creek Canyons Study
All Sites
Baseflow Conditions

Group		pH	TDS (mg/L)	Turbidity (ftu)	NH3-N (mg/L)	NO3-N (mg/L)	Ortho-P (mg/L)	Fecal Coliform (col/100 mL)	TSS (mg/L)	Flow (cfs)	Temperature °C
Golf	count	54	54	30	61	66	64	20	37	25	10
Golf	minimum	6.90	240	0.50	0.005	0.01	0.0005	1	0.25	0.0005	18.00
Golf	maximum	8.40	828	8.00	0.13	2.16	0.17	4300	15.00	4.27	25.00
Golf	mean	7.82	452	2.66	0.02	0.68	0.03	576	3.44	0.53	21.32
Golf	median	7.90	440	2.00	0.01	0.63	0.03	69	2.00	0.05	21.60
Residential	count	91	92	66	94	99	97	60	52	42	16
Residential	minimum	7.16	170	0.50	0.005	0.005	0.0005	1	0.25	0.0005	14.00
Residential	maximum	8.38	678	6.00	0.40	4.20	0.90	3300	13.00	3.50	26.50
Residential	mean	7.90	351	1.78	0.03	0.54	0.03	330	2.08	0.45	21.54
Residential	median	7.90	349	1.00	0.01	0.20	0.02	91	1.00	0.10	21.60
Rural	count	43	42	40	48	55	52	33	19	28	10
Rural	minimum	7.40	210	0.50	0.005	0.005	0.0005	1	0.25	0.0001	15.00
Rural	maximum	8.52	490	4.00	0.10	0.80	0.09	6000	5.00	12.71	31.00
Rural	mean	7.86	284	1.33	0.01	0.08	0.02	369	1.16	1.83	23.70
Rural	median	7.82	272	1.00	0.01	0.05	0.02	40	0.25	0.58	24.50

Source: COA / DUD Database 1993 - 1995

Table 3.8

Barton Creek Canyons Study
Representative Canyons
Baseflow, Stormflow and Post Stormflow Conditions

Site	Group	Flow		pH	TDS (mg/L)	Turbidity (ftu)	NH3-N (mg/L)	NO3-N (mg/L)	Ortho-P (mg/L)	Fecal Coliform (col/100 mL)	TSS (mg/L)	Flow (cfs)	Temperature °C
CRT1	Golf	Baseflow	count	19	19	16	21	23	21	12	10	7	0
CRT1	Golf	Baseflow	minimum	7.60	330	1.00	0.005	0.05	0.005	3	0.25	0.0005	
CRT1	Golf	Baseflow	maximum	8.30	535	8.00	0.13	1.50	0.17	4300	5.00	0.86	
CRT1	Golf	Baseflow	mean	7.95	414	2.61	0.03	0.87	0.05	742	1.19	0.13	
CRT1	Golf	Baseflow	median	7.90	420	2.00	0.008	0.90	0.04	82	0.25	0.01	
CRT	Golf	Post Stormflow	count	2	2	2	2	2	2	1	2	1	0
CRT	Golf	Post Stormflow	minimum	7.50	270	3.00	0.005	1.50	0.04	630	2.60	0.03	
CRT	Golf	Post Stormflow	maximum	7.80	480	27.00	0.16	1.90	0.50	630	3.50	0.03	
CRT	Golf	Post Stormflow	mean	7.65	375	15.00	0.08	1.70	0.27	630	3.05	0.03	
CRT	Golf	Post Stormflow	median	7.65	375	15	0.08	1.70	0.27	630	3.05	0.03	
CRT	Golf	Stormflow	count	5	5	5	5	5	5	3	2	1	0
CRT	Golf	Stormflow	minimum	7.60	280	0.75	0.02	0.90	0.05	165	0.80	0.004	
CRT	Golf	Stormflow	maximum	8.10	400	158.50	0.27	1.30	2.50	13650	1.20	0.004	
CRT	Golf	Stormflow	mean	7.82	334	43.85	0.13	1.10	0.59	7938	1.00	0.004	
CRT	Golf	Stormflow	median	7.90	320	21.50	0.13	1.05	0.06	10000	1.00	0.004	
RRC	Residential	Baseflow	count	17	17	16	17	18	18	16	12	11	1
RRC	Residential	Baseflow	minimum	7.76	220	0.50	0.01	0.30	0.01	20	0.25	0.001	21.20
RRC	Residential	Baseflow	maximum	8.30	420	6.00	0.08	2.20	0.05	1900	4.70	1.79	21.20
RRC	Residential	Baseflow	mean	8.03	347	1.81	0.03	1.30	0.03	449	1.57	0.30	21.20
RRC	Residential	Baseflow	median	8.09	360	1.00	0.02	1.25	0.03	167	1.30	0.03	21.20
RRC	Residential	Post Stormflow	count	3	3	3	3	3	3	3	2	3	0
RRC	Residential	Post Stormflow	minimum	7.60	240	3.00	0.005	1.35	0	300	0.25	0.15	
RRC	Residential	Post Stormflow	maximum	8.20	400	5.50	0.06	1.80	0	950	1.30	2.09	
RRC	Residential	Post Stormflow	mean	7.87	340	4.17	0.03	1.65	0	563	0.78	0.81	
RRC	Residential	Post Stormflow	median	7.80	380	4.00	0.02	1.80	0	440	0.78	0.18	
RRC	Residential	Stormflow	count	5	5	5	5	5	5	4	3	3	0
RRC	Residential	Stormflow	minimum	7.70	80	0.75	0.01	0.36	0.02	144	0.25	0.003	
RRC	Residential	Stormflow	maximum	8.30	350	242.00	0.36	0.95	0.35	55000	15.20	0.25	
RRC	Residential	Stormflow	mean	8.00	233	57.95	0.11	0.64	0.15	16114	5.32	0.09	
RRC	Residential	Stormflow	median	8.00	225	9.00	0.04	0.60	0.04	4655	0.50	0.008	
SSBE	Rural	Baseflow	count	12	12	11	13	14	13	11	11	9	0
SSBE	Rural	Baseflow	minimum	7.60	270	0.50	0.005	0.005	0.005	1	0.25	0.02	
SSBE	Rural	Baseflow	maximum	8.11	490	4.00	0.10	0.80	0.05	6000	4.80	4.27	
SSBE	Rural	Baseflow	mean	7.83	346	1.32	0.02	0.14	0.02	578	0.90	1.20	
SSBE	Rural	Baseflow	median	7.80	326	1.00	0.01	0.08	0.02	40	0.25	0.76	
SSBE	Rural	Post Stormflow	count	2	2	2	2	2	2	2	2	2	0
SSBE	Rural	Post Stormflow	minimum	7.80	230	1.00	0.005	0.05	0.005	1	0.25	0.39	
SSBE	Rural	Post Stormflow	maximum	8.10	330	2.00	0.02	0.10	0.02	190	2.20	2.88	
SSBE	Rural	Post Stormflow	mean	7.95	280	1.50	0.01	0.08	0.01	95	1.23	1.64	
SSBE	Rural	Post Stormflow	median	7.95	280	1.50	0.01	0.08	0.01	95	1.23	1.64	
SSBE	Rural	Stormflow	count	4	4	4	4	4	4	3	3	2	0
SSBE	Rural	Stormflow	minimum	7.60	310	0.50	0.01	0.09	0.005	69	0.25	0.04	
SSBE	Rural	Stormflow	maximum	7.70	430	10.00	0.12	0.20	0.04	1070	2.20	0.15	
SSBE	Rural	Stormflow	mean	7.68	378	4.25	0.04	0.14	0.02	446	1.22	0.09	
SSBE	Rural	Stormflow	median	7.70	385	3.25	0.02	0.14	0.03	200	1.20	0.09	

Source: COA / DUD Database 1993 - 1995

Table 3.9

Barton Creek Canyons Study
Two Different Buffers
Baseflow and Stormflow Conditions

Group	Flow		pH	TDS (mg/L)	Turbidity (ftu)	NH3-N (mg/L)	NO3-N (mg/L)	Ortho-P (mg/L)	Fecal Coliform (col/100 mL)	TSS (mg/L)	Flow (cfs)	Temperature °C
LCR	Baseflow	count	13	13	11	13	13	13	12	9	2	0
LCR	Baseflow	minimum	7.16	250	0.50	0.005	0.005	0.005	1	0.25	0.06	
LCR	Baseflow	maximum	8.34	390	6.00	0.10	1.80	0.06	3300	5.25	0.11	
LCR	Baseflow	mean	7.63	335	2.86	0.02	0.31	0.03	471	1.38	0.09	
LCR	Baseflow	median	7.60	330	3.00	0.02	0.13	0.03	95	1.00	0.09	
RRC	Baseflow	count	17	17	16	17	18	18	16	12	11	1
RRC	Baseflow	minimum	7.76	220	0.50	0.01	0.30	0.01	20	0.250	0.001	21.20
RRC	Baseflow	maximum	8.30	420	6.00	0.08	2.20	0.05	1900	4.700	1.790	21.20
RRC	Baseflow	mean	8.03	347	1.81	0.03	1.30	0.03	449	1.574	0.303	21.20
RRC	Baseflow	median	8.09	360	1.00	0.02	1.25	0.03	167	1.300	0.026	21.20
LCR	Stormflow	count	3	3	3	3	3	3	2	2	1	0
LCR	Stormflow	minimum	7.23	184	5.00	0.01	0.06	0.020	135	0.25	0.04	
LCR	Stormflow	maximum	7.60	350	7.00	0.09	0.60	0.070	3800	1.00	0.04	
LCR	Stormflow	mean	7.44	281	6.00	0.04	0.35	0.040	1968	0.63	0.04	
LCR	Stormflow	median	7.50	310	6.00	0.02	0.40	0.030	1968	0.63	0.04	
RRC	Stormflow	count	5	5	5	5	5	5	4	3	3	0
RRC	Stormflow	minimum	7.70	80	0.75	0.010	0.36	0.02	144	0.25	0.003	
RRC	Stormflow	maximum	8.30	350	242.00	0.360	0.95	0.35	55000	15.20	0.25	
RRC	Stormflow	mean	8.00	233	57.95	0.106	0.64	0.15	16114	5.32	0.09	
RRC	Stormflow	median	8.00	225	9.00	0.040	0.60	0.04	4655	0.50	0.01	

Source: COA / DUD Database 1993 - 1995

Table 3.10

Barton Creek Canyons Study
Alternative Wastewater Strategies
Baseflow Conditions

Group	Flow	pH	TDS (mg/L)	Turbidity (ftu)	NH3-N (mg/L)	NO3-N (mg/L)	Ortho-P (mg/L)	Fecal Coliform (col/100 mL)	TSS (mg/L)	Flow (cfs)	Temperature °C
GEI	count	54	54	30	61	66	64	20	37	25	10
GEI	minimum	6.90	240	0.50	0.01	0.01	0.001	1	0.25	0.0005	18.00
GEI	maximum	8.40	828	8.00	0.13	2.16	0.170	4300	15.00	4.27	25.00
GEI	mean	7.82	452	2.66	0.02	0.68	0.031	576	3.44	0.53	21.32
GEI	median	7.90	440	2.00	0.01	0.63	0.029	69	2.00	0.05	21.60
RC	count	48	49	40	48	51	49	43	35	18	3
RC	minimum	7.16	220	0.50	0.01	0.01	0.001	1	0.25	0.0005	19.00
RC	maximum	8.34	506	6.00	0.10	2.29	0.060	3300	7.40	1.80	21.20
RC	mean	7.87	338	2.06	0.02	0.78	0.025	382	1.58	0.36	20.40
RC	median	7.90	337	1.00	0.01	0.60	0.020	100	1.00	0.05	21.00
REI	count	17	17	12	17	17	17	11	4	11	7
REI	minimum	7.42	230	0.50	0.01	0.05	0.001	1	0.50	0.05	14.00
REI	maximum	8.38	564	3.00	0.40	4.20	0.900	1300	5.00	3.50	26.50
REI	mean	7.91	385	1.00	0.03	0.47	0.074	258	2.73	0.71	22.00
REI	median	7.90	387	1.00	0.01	0.21	0.020	110	2.70	0.17	24.00
RS	count	26	26	14	29	31	31	6	13	13	6
RS	minimum	7.40	170	0.50	0.01	0.01	0.001	1	0.25	0.002	18.00
RS	maximim	8.30	678	4.00	0.23	1.20	0.105	470	13.00	2.50	23.89
RS	mean	7.94	353	1.64	0.03	0.19	0.020	89	3.23	0.37	21.58
RS	median	8.00	329	1.50	0.01	0.08	0.010	8	2.00	0.08	22.10
Rural	count	43	42	40	48	55	52	33	19	28	10
Rural	minimum	7.40	210	0.50	0.005	0.005	0.0005	1	0.25	0.0001	15.00
Rural	maximum	8.52	490	4.00	0.10	0.80	0.090	6000	5.00	12.71	31.00
Rural	mean	7.86	284	1.33	0.01	0.08	0.023	369	1.16	1.83	23.70
Rural	median	7.82	272	1.00	0.01	0.05	0.016	40	0.25	0.58	24.50

Source: COA / DUD Database 1993 - 1995

Table 3.11
Barton Creek Canyons Study
Overview of Statistically Significant Variables

	Nonparametric Tests		Multiple Comparison Test		
Crenshaw Tributary (Golf) Ringtail Ridge Canyon (Residential) Short Springs Branch Estates (Rural)	**Means**	**Medians**	**Golf vs Residential**	**Golf vs Rural**	**Residential vs Rural**
Baseflow	pH, TDS, Turbidity, NO3-N, Ortho-P, Fecal Coliform, Flow	pH, TDS, Turbidity, NO3-N, Ortho-P, Fecal Coliform, Flow	TDS, Turbidity, NO3-N, Ortho-P	TDS, Turbidity, NO3-N, Ortho-P, Flow	pH, NO3-N, NH3-N, Fecal Coliform, Flow
Stormflow	TDS, NO3-N, Ortho-P	NO3-N, Ortho-P	NO3-N	NO3-N, Ortho-P	pH, TDS, NO3-N

	Nonparametric Tests		Multiple Comparison Test		
All Sites Consolidated into Golf, Residential & Rural Groups	**Means**	**Medians**	**Golf vs Residential**	**Golf vs Rural**	**Residential vs Rural**
Baseflow	TDS, Turbidity, NO3-N, TSS, Flow	TDS, Turbidity, NO3-N, TSS, Flow	TDS, Turbidity, NO3-N, TSS	TDS, Turbidity, NO3-N, TSS, Flow	TDS, Turbidity, NH3-N, NO3-N, Flow

	Nonparametric Tests		Multiple Comparison Test			
Alternative Wastewater Sites: Golf Effulent Irrigated (GEI) Residential Effluent Irrigated (REI) Residential Septic (RS) Residential Central (RC) Rural (R)	**Means**	**Medians**	**Rural vs GEI**	**Rural vs RC**	**Rural vs REI**	**Rural vs RS**
Baseflow	TDS, Turbidity, NO3-N, TSS, Flow	TDS, Turbidity, NO3-N, TSS	TDS, Turbidity, NO3-N, TSS, Flow	TDS, NO3-N, NH3-N, TSS, Flow	TDS, NO3-N, TSS	pH, TDS, TSS

	Nonparametric Tests	
Two Different Buffers: Lost Creek Residential Ringtail Ridge Canyon	**Means**	**Medians**
Baseflow	pH, NO3-N	pH, NO3-N

change any fundamental interpretation of the data. Additional study is planned in order to verify the relationships noted thus far.

3.3.4 Discussion of Results

3.3.4.1 Flow

Flows ranging from <0.01 to 12.71 cfs were measured during baseflow conditions in all 38 tributaries to Barton Creek. The three representative tributaries' average baseflow ranged as follows: 0.11 cfs at CRT1 (golf), 0.28 cfs at RRC (residential), and 1.2 cfs at SSBE (rural). The median flows for CRT1, RRC, and SSBE are lower at 0.03, 0.04, and 0.76 cfs respectively. These flows reflect the size of the three watersheds: CRT1 is 22.9 acres, RRC is 72.1 acres, and SSBE is 1,904.8 acres. Analyses indicate that there was no significant difference between baseflow in CRT1 and RRC, but SSBE flows were significantly higher than the other two representative tributaries.

One significant storm event monitored on the three representative tributaries, generating considerable runoff, occurred on 5/13/94; however, no flow measurements were obtained during this event because of equipment shortage. Other storm events generated little more flow than is typically measured during baseflow events; although, enough runoff was generated to affect turbidity and other water quality parameters. The highest stormflow measured in any of the 38 Barton tributaries over the course of this study was 61.47 cfs, and this measurement was made at the mouth of a large rural tributary about 12 hours after three consecutive days of rain, totaling approximately six inches.

It is interesting that both representative tributaries for golf and residential land use maintained some baseflow throughout the year even though their drainage areas are considerably smaller than the representative rural tributary (SSBE). In fact, during several particularly dry months, the SSBE was dry, while the two developed tributaries (RRC and CRT1) maintained a small flow. It may be possible that certain types of development which are characterized by heavy summer irrigation may enhance baseflow to their respective drainage ways. Further study of this anomaly is warranted. None of the statistical analyses accounted for the drainage area of the tributaries, and comparisons of flow in this section were made only as another water quality variable. An analysis of watershed yield, comparing tributaries with alternative wastewater strategies, is discussed in Section 2.3.

3.3.4.2 pH

During baseflow and stormflow conditions a significant difference in pH was observed between the representative residential (RRC) and representative rural (SSBE) tributaries (Figure 3.16); although, no significant differences in pH were evident when comparing the three principal land uses at all 38 sites. Comparing baseflow pH in canyons using different wastewater treatment strategies, the residential septic (RS) sites were significantly higher in pH compared to rural (R) sites (Figure 3.17). Comparing the two residential sites with different sized buffers, RRC, with the smallest buffer, was significantly higher in pH than large buffered LCR during both baseflow and stormflow conditions (Figure 3.18).

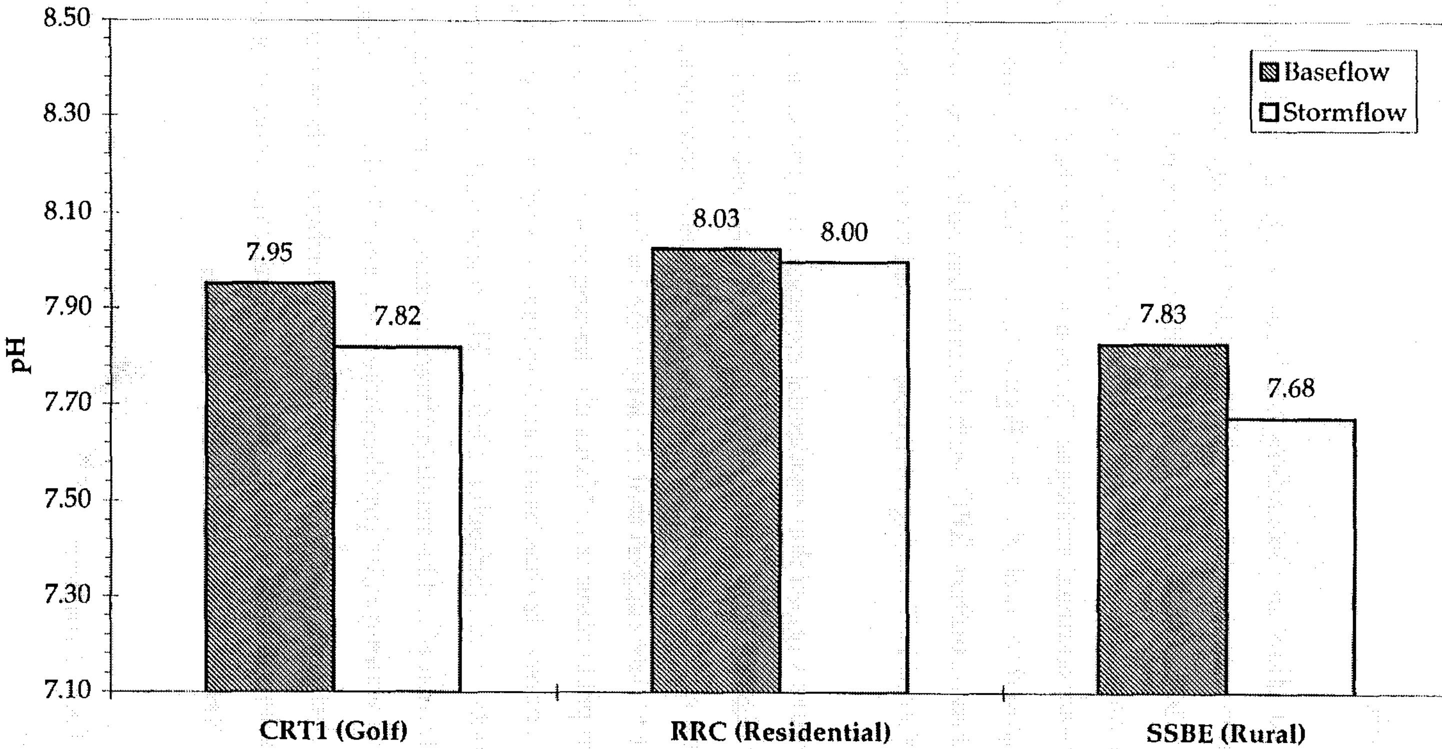
These results suggest that residential canyons on septic systems or residential watersheds that use high pH city water (> 9 pH units) (COA 1994a) for lawn irrigation may be impacting water quality by making surface waters more basic. Furthermore, the data available to date suggest that the larger the buffer zone around the creek, the less this impact in pH is observed. Naturally, testing at several buffer levels is needed to verify this; however, buffer size has been found to have a similar relationship to water quality in studies nationwide (Schueler, 1995a). The residential canyon with the largest buffer zone had the lowest pH. The small buffered stream's higher average baseflow pH of 8.03 is not a significant water quality problem however, since TNRCC's ambient water quality criteria for pH is between 6.5 and 9.0 pH units. Nevertheless, these results indicate that high pH may be a signature of watersheds where significant amounts of irrigation is practiced using treated potable water from the City of Austin.

3.3.4.3 Fecal Coliform

Comparisons among golf, residential, and rural land use for median fecal coliform concentrations during baseflow are shown in Figure 3.19 for all 38 sites. Figure 3.20 shows

Figure 3.16

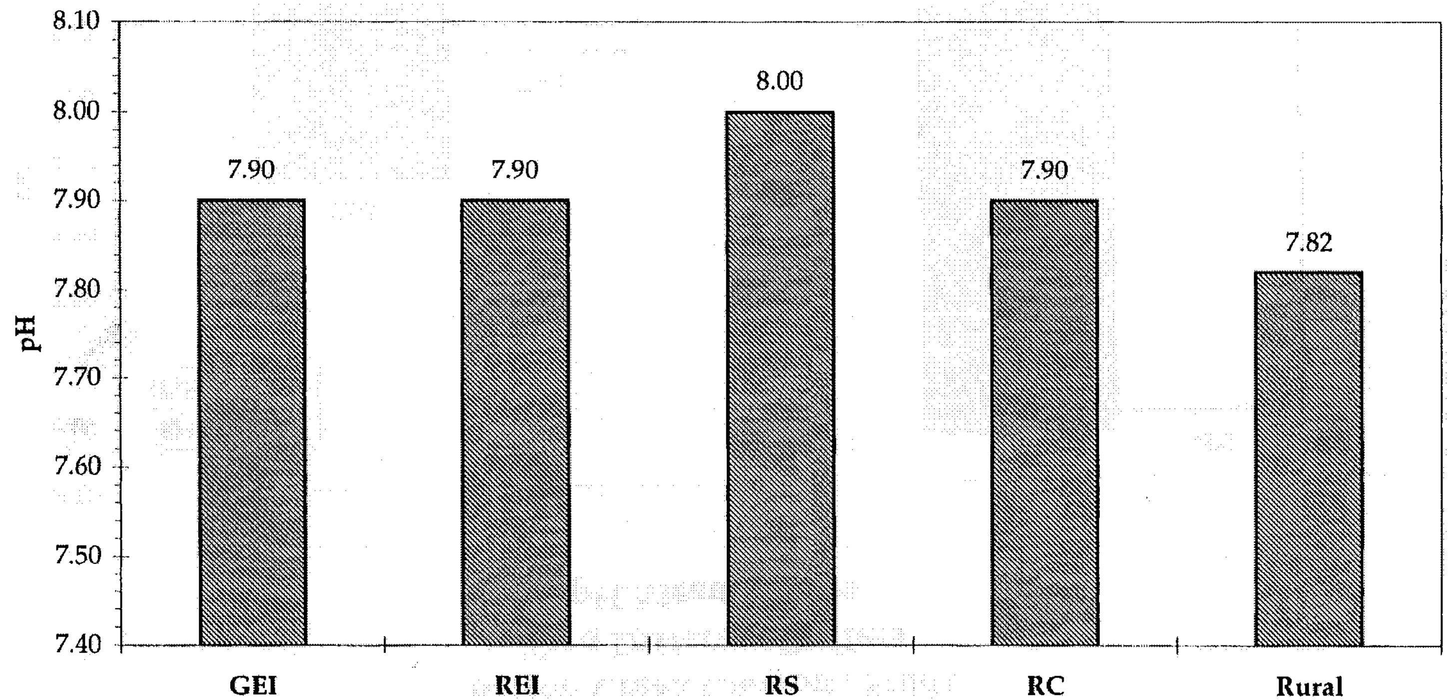
Barton Creek Canyons Study
Three Representative Tributaries
pH Mean Values



Source: COA / DUD Database 1993 - 1995

Figure 3.17

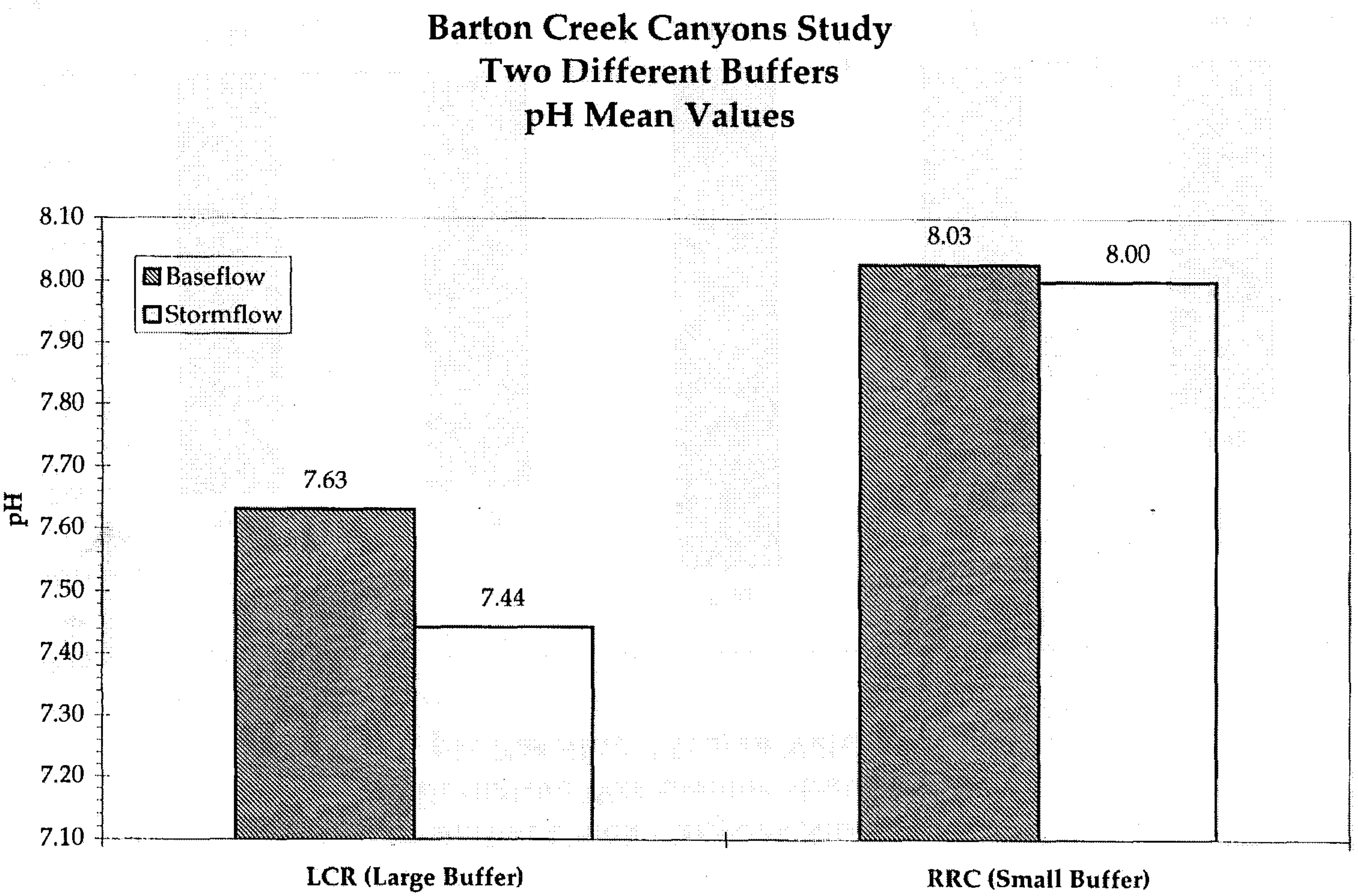
Barton Creek Canyons Study
Alternative Wastewater Strategies
pH Baseflow Median Values



GEI - Golf Effluent Irrigated
REI - Residential Effluent Irrigated
RS - Residential Septic
RC - Residential Central
Rural - Undeveloped

Source: COA/ DUD Database 1993 - 1995

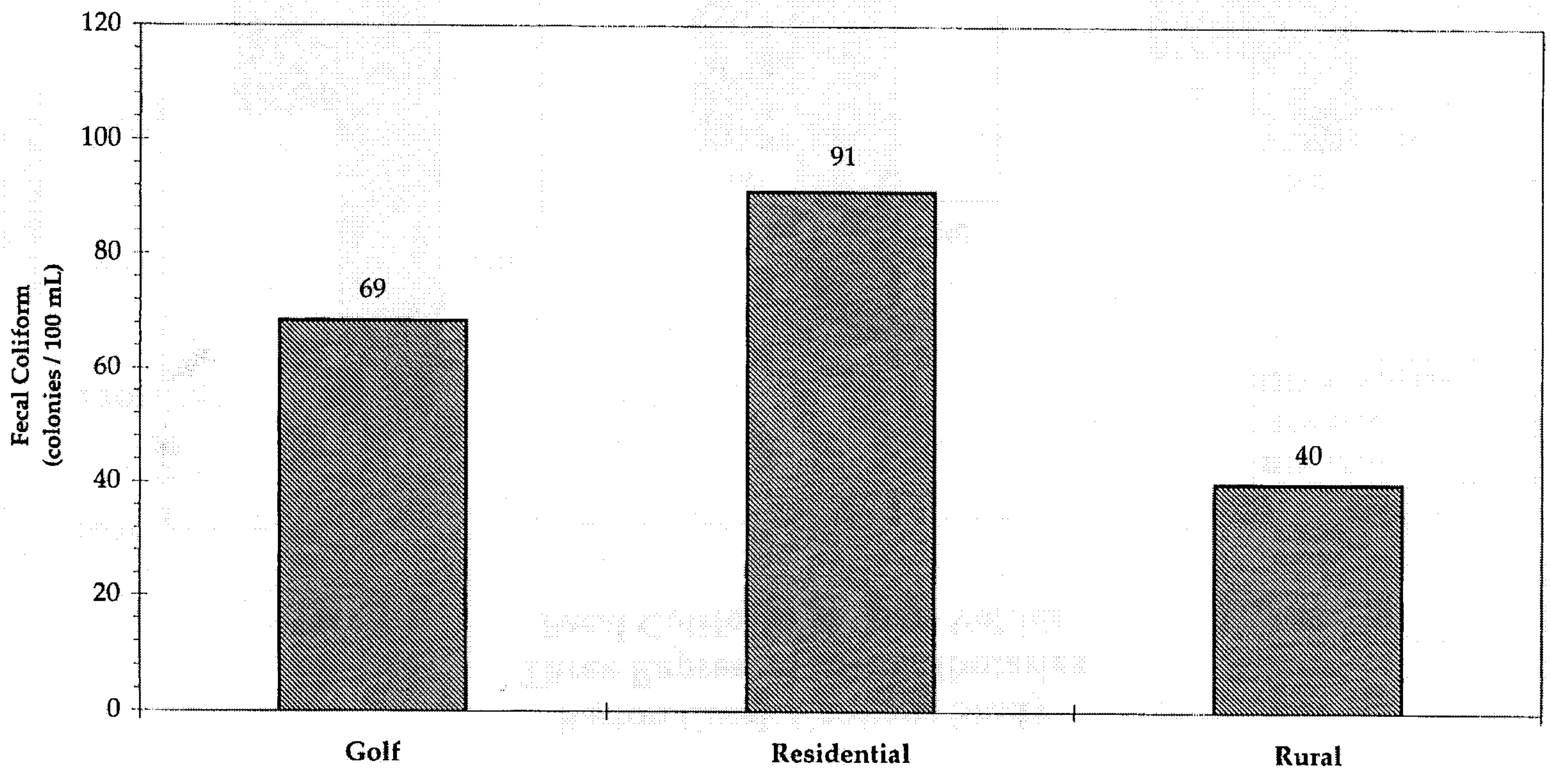
Figure 3.18



Source: COA / DUD Database 1993 - 1995

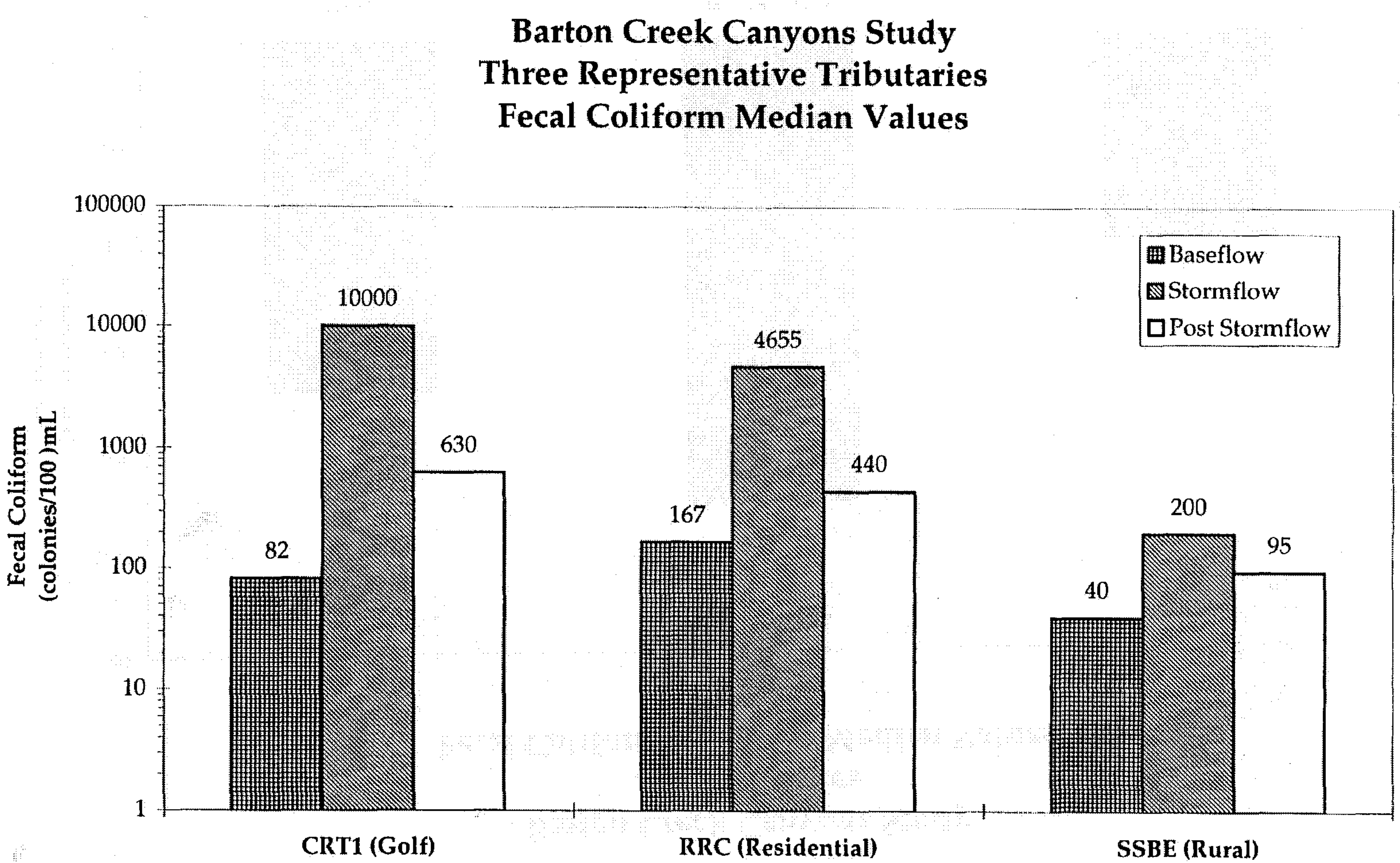
Figure 3.19

Barton Creek Canyons Study
All Tributaries
Fecal Coliform Baseflow Median Values



Source: COA/DUD Database 1993 - 1995

Figure 3.20



Source: COA / DUD Database 1993 - 1995

fecal values during baseflow, stormflow, and post stormflow for the three representative tributaries. No significant differences are found in baseflow bacteria concentrations when examining all 38 sites, sites using alternative wastewater strategies, or residential canyons with different sized buffer zones. The only statistically significant difference occurred between baseflow fecal concentrations in the representative residential stream (RRC) and the representative rural stream (SSBE) where median values were 167 and 40 col./100ml, respectively. Median fecal concentrations appeared to be substantially different during and immediately after storm events among the three representative land uses; however, these differences are not statistically significant (Figure 3.20).

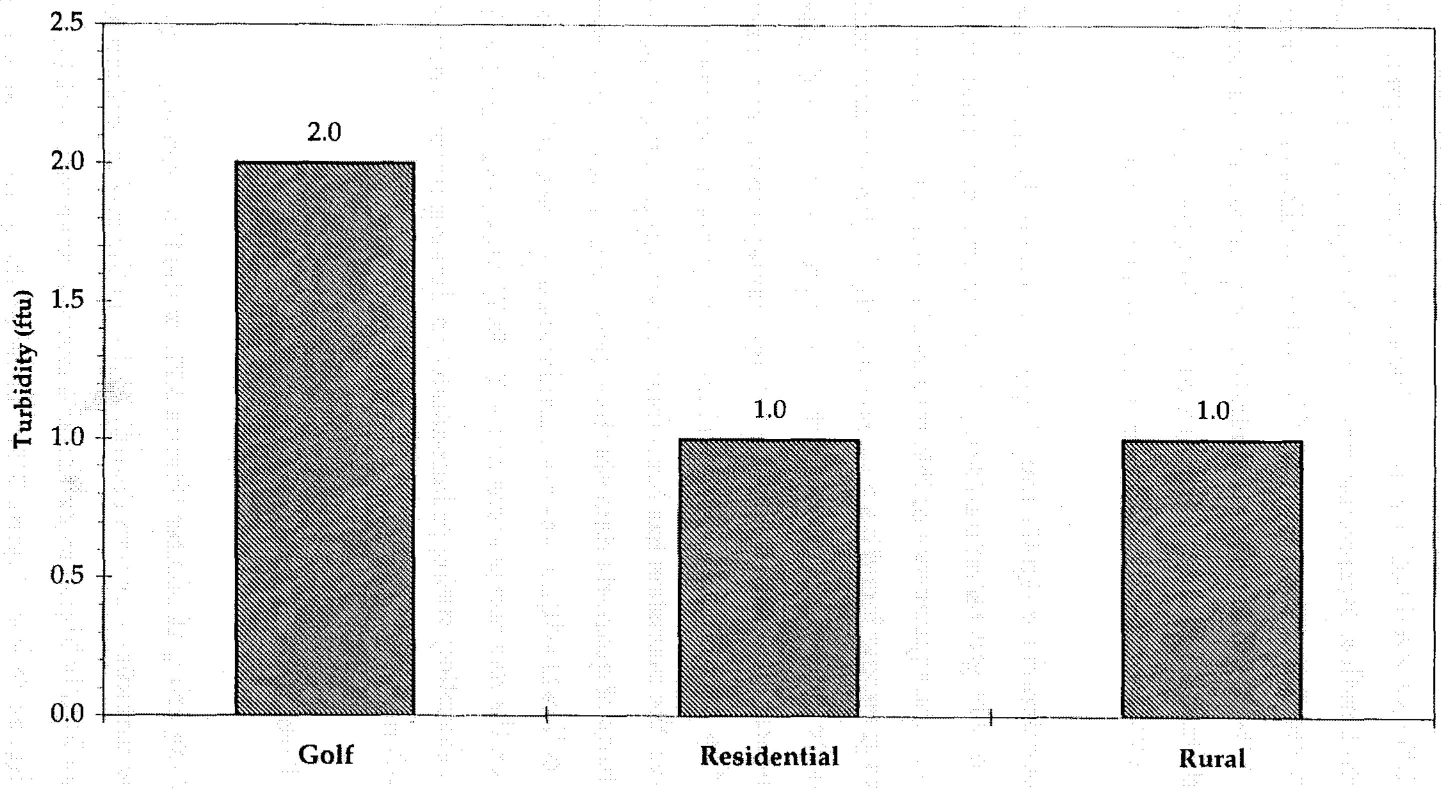
One speculation for significantly higher bacteria in the representative residential canyon (RRC) may be greater amounts of pet feces from concentrated subdivision developments. However, the significance of this statistical difference may be an anomaly, because no other analysis grouping found bacteria significantly higher in residential areas. Whatever the reasons for higher fecal counts in this one representative residential tributary, the baseflow median fecal coliform levels were not high enough to warrant a persistent health threat (as defined by TNRCC standards) to citizens using these waters recreationally (Appendix E). However, the mainstem has been found to not support the contact recreation use category on the basis of quarterly data obtained from eight TNRCC monitoring sites. This excedance of fecal coliform criteria was not corroborated by the City's mainstem perennial pool data. However, the location of some of the TNRCC sites (below Barton Springs pool) as well as TNRCC sampling during or immediately following storm events may have contributed to the excedances.

3.3.4.4 Turbidity and Total Suspended Solids

When comparing all 38 sites (Figure 3.21) or the three representative sites (Figure 3.22), baseflow turbidity was significantly higher in the golf course canyons. Baseflow TSS was also significantly higher in golf course canyons than residential or rural canyons when comparing all 38 sites (Figure 3.23); however, there was no significant difference in TSS when comparing baseflow in the three representative canyons.

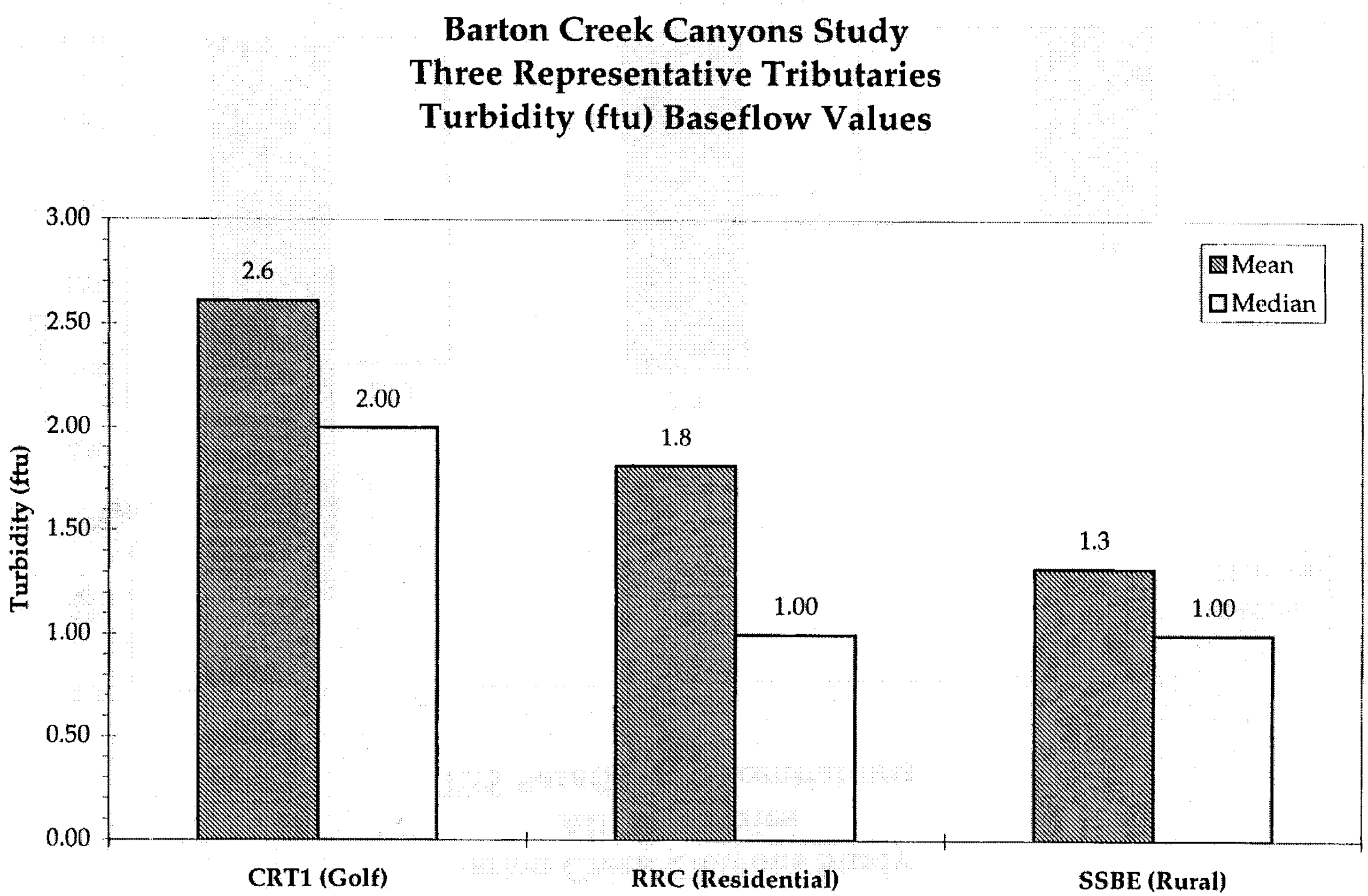
Figure 3.21

Barton Creek Canyons Study
All Tributaries
Turbidity Baseflow Median Values



Source: COA/DUD Database 1993 - 1995

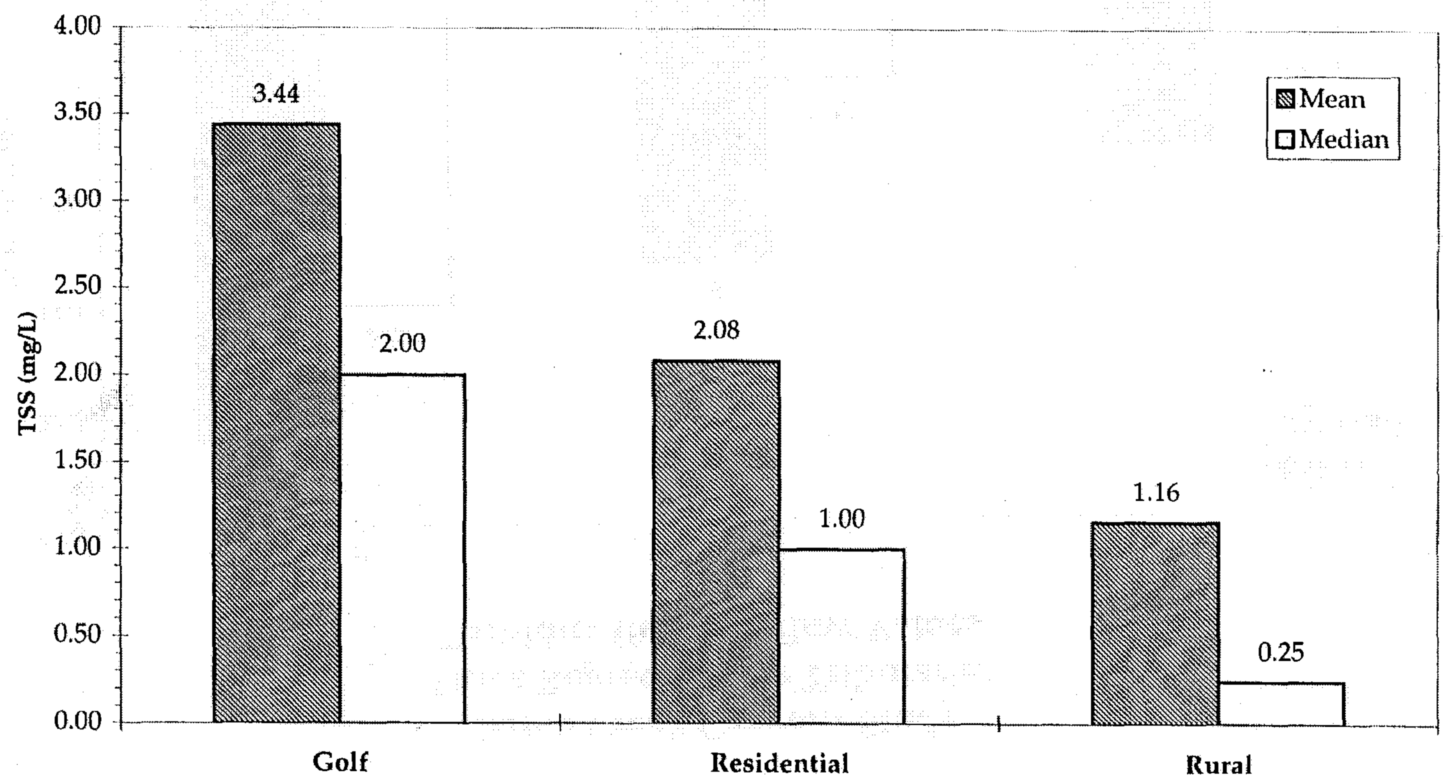
Figure 3.22



Source: COA / DUD Database 1993 - 1995

Figure 3.23

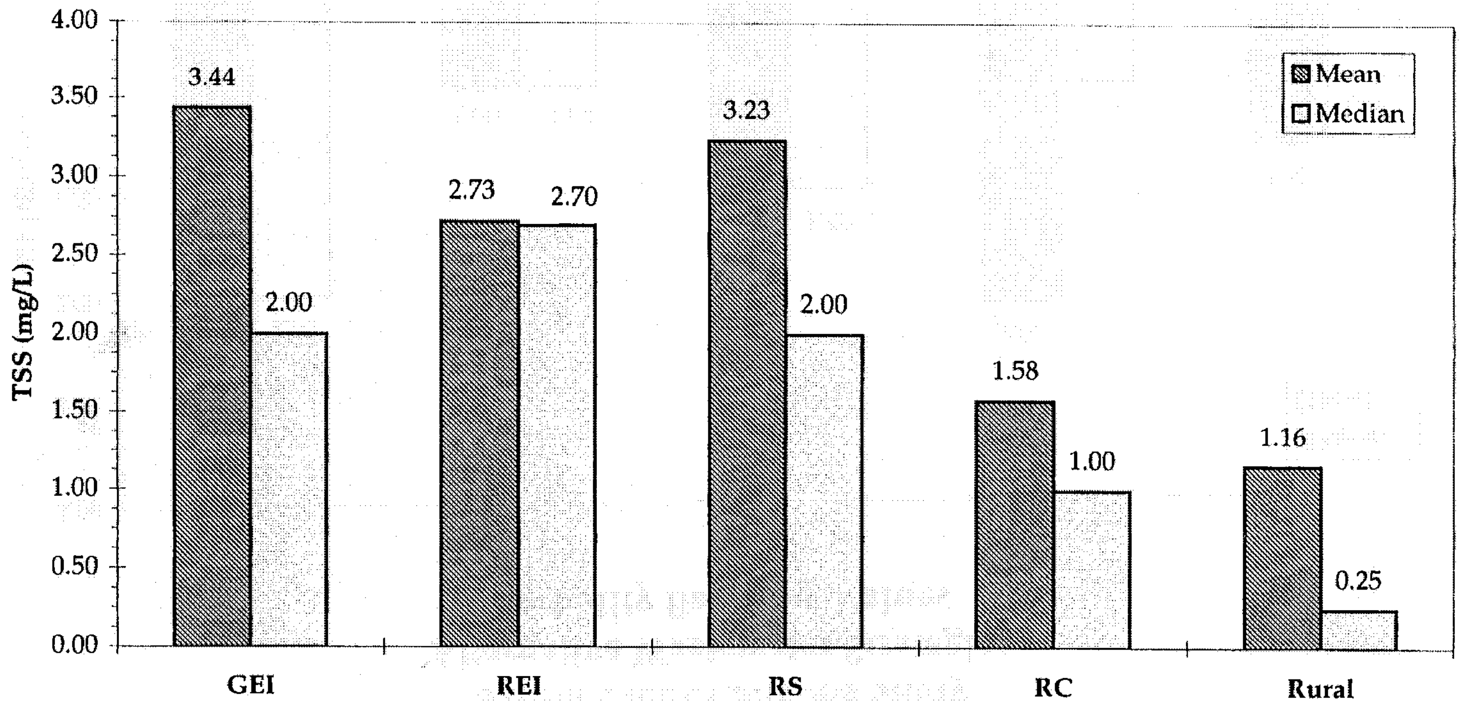
Barton Creek Canyons Study
All Tributaries
TSS Baseflow Concentrations



Source: COA/DUD Database 1993 - 1995

Figure 3.24

Barton Creek Canyons Study
Alternative Wastewater Strategies
TSS Baseflow Concentrations

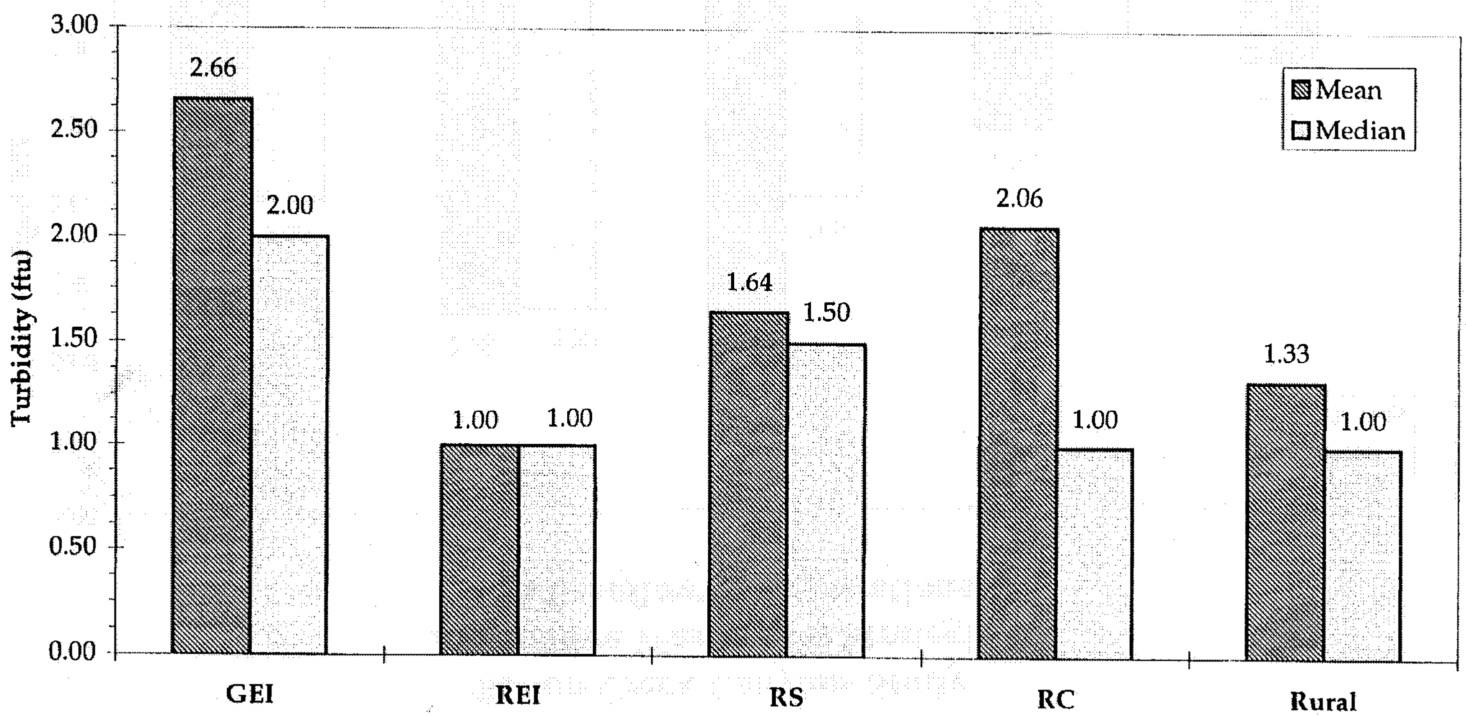


GEI - Golf Effluent Irrigated
REI - Residential Effluent Irrigated
RS - Residential Septic
RC - Residential Central
Rural - Undeveloped

Source: COA/ DUD Database 1993 - 1995

Figure 3.25

Barton Creek Canyons Study
Alternative Wastewater Strategies
Turbidity Baseflow Values



GEI - Golf Effluent Irrigated
REI - Residential Effluent Irrigated
RS - Residential Septic
RC - Residential Central
Rural - Undeveloped

Source: COA/ DUD Database 1993 - 1995

The various wastewater alternative land uses (GEI, REI, RS, and RC) were all significantly higher in average TSS when comparing baseflow with rural (R) watersheds (Figure 3.24), but only the golf course effluent irrigated (GEI) streams had significantly higher baseflow turbidity than rural tributaries (Figure 3.25). No significant differences in turbidity or TSS were indicated between the three principal land uses during stormflow conditions, and there were no significant differences in either parameter between the two residential canyons with different sized buffer zones during baseflow or stormflow.

3.3.4.5 Ammonia

Some significant and unusual differences in ammonia concentrations were found in baseflow when comparing the three principal land uses. Although no significant differences were found in ammonia in baseflow or stormflow when comparing the three representative canyons, a significant difference was indicated between rural streams and residential streams when comparing all 38 sites (Figure 3.26). When analyzing alternative wastewater strategies, a significant difference was also indicated between residential streams on central systems and rural streams. No significant differences were seen in ammonia concentrations between the two streams with different sized buffers. Significance may be in question when analyzing ammonia data since most results are at or below the detection limit.

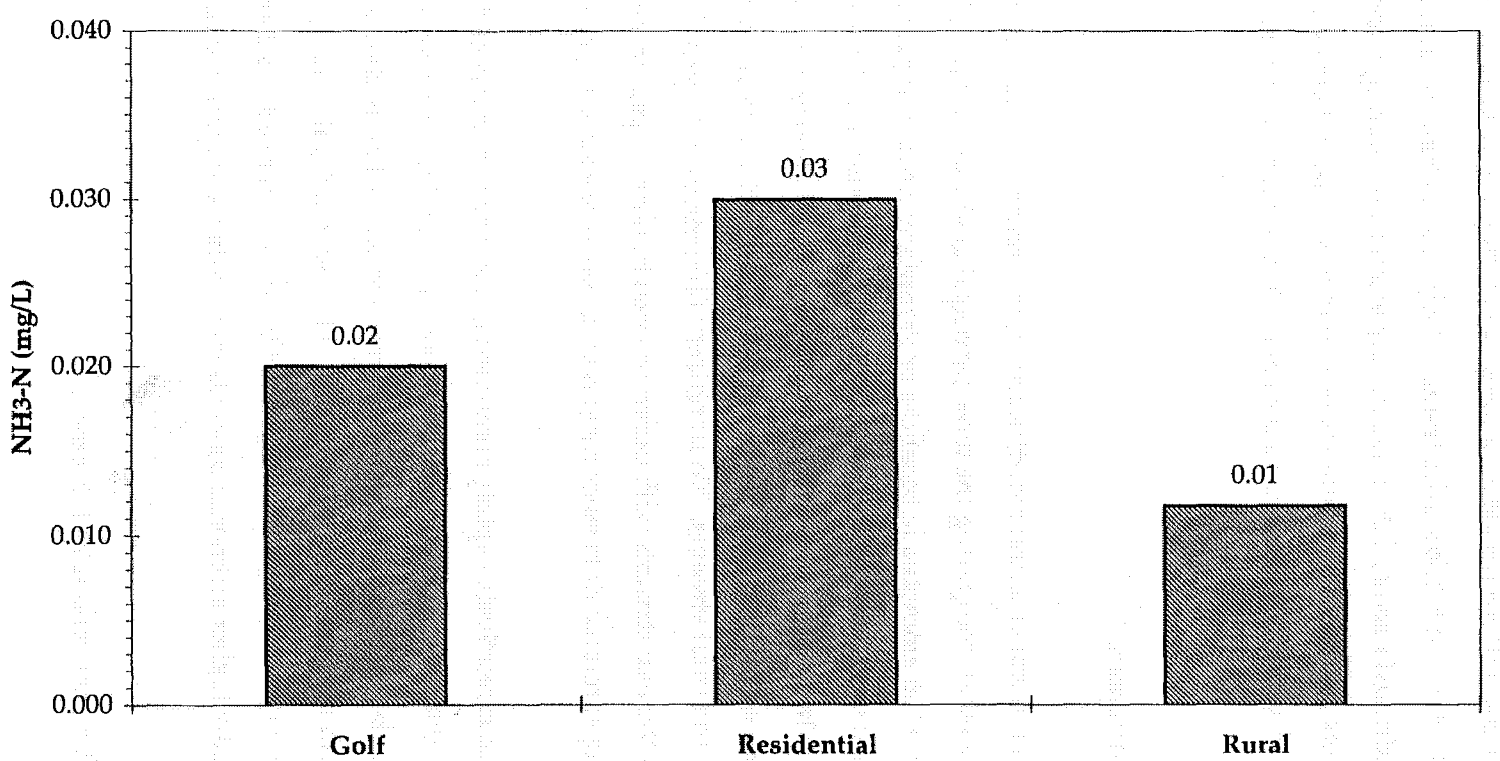
Ammonia is relatively rapidly converted or oxidized to nitrite and nitrate when in contact with oxygen; therefore, ammonia was usually found in very low concentrations. This is the reason for baseflow median ammonia concentrations below the detection limit of 0.01 mg/L for all land uses analyzed in this study. However, irrigation with treated City water, relatively high in ammonia nitrogen (COA, 1994a), in residential areas may account for its significantly higher ammonia concentrations when compared to rural areas.

3.3.4.6 Orthophosphate as P (Ortho-P)

Like ammonia levels, baseflow ortho-P was usually found in very low concentrations, but this study indicates that baseflow ortho-P was significantly higher in the representative golf

Figure 3.26

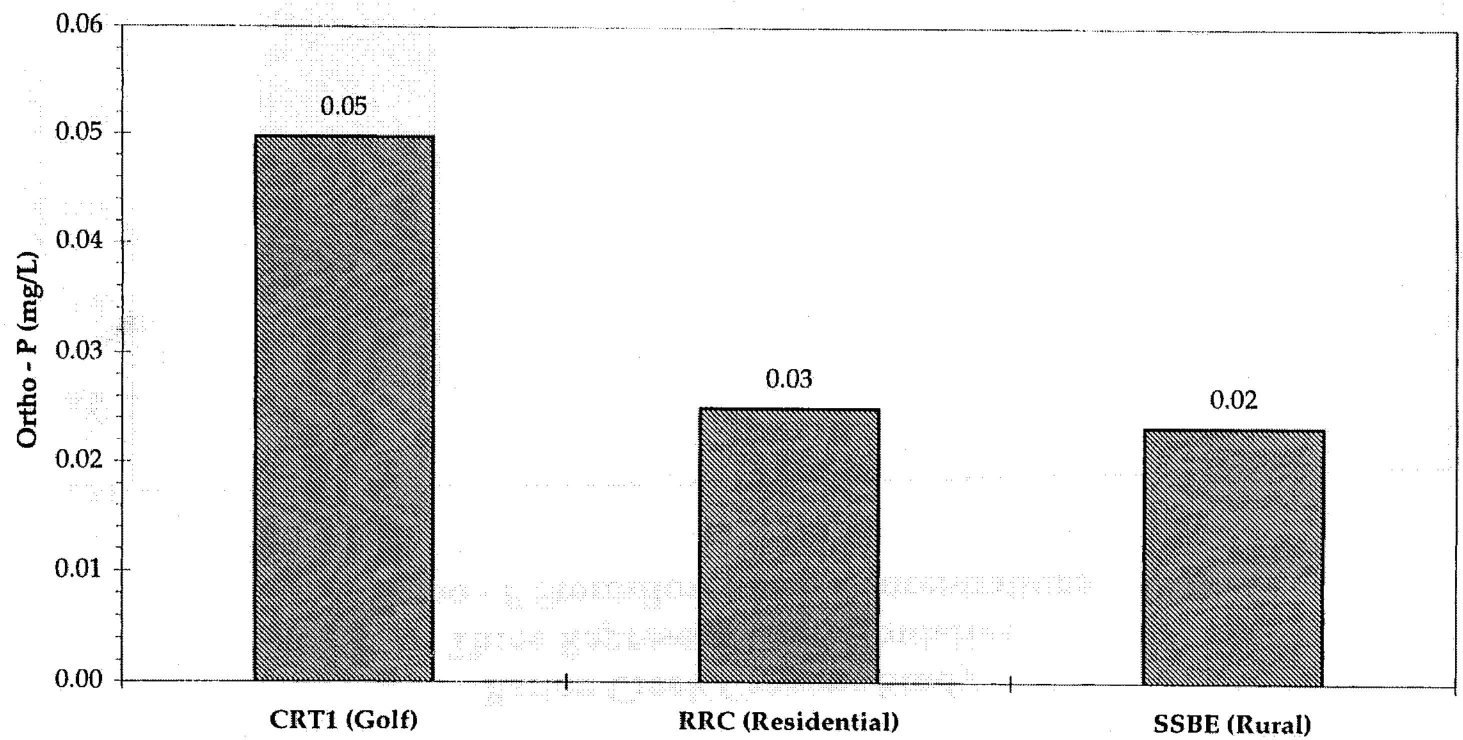
Barton Creek Canyons Study
All Tributaries
NH3-N Baseflow Mean Concentrations



Source: COA/DUD Database 1993 - 1995

Figure 3.27

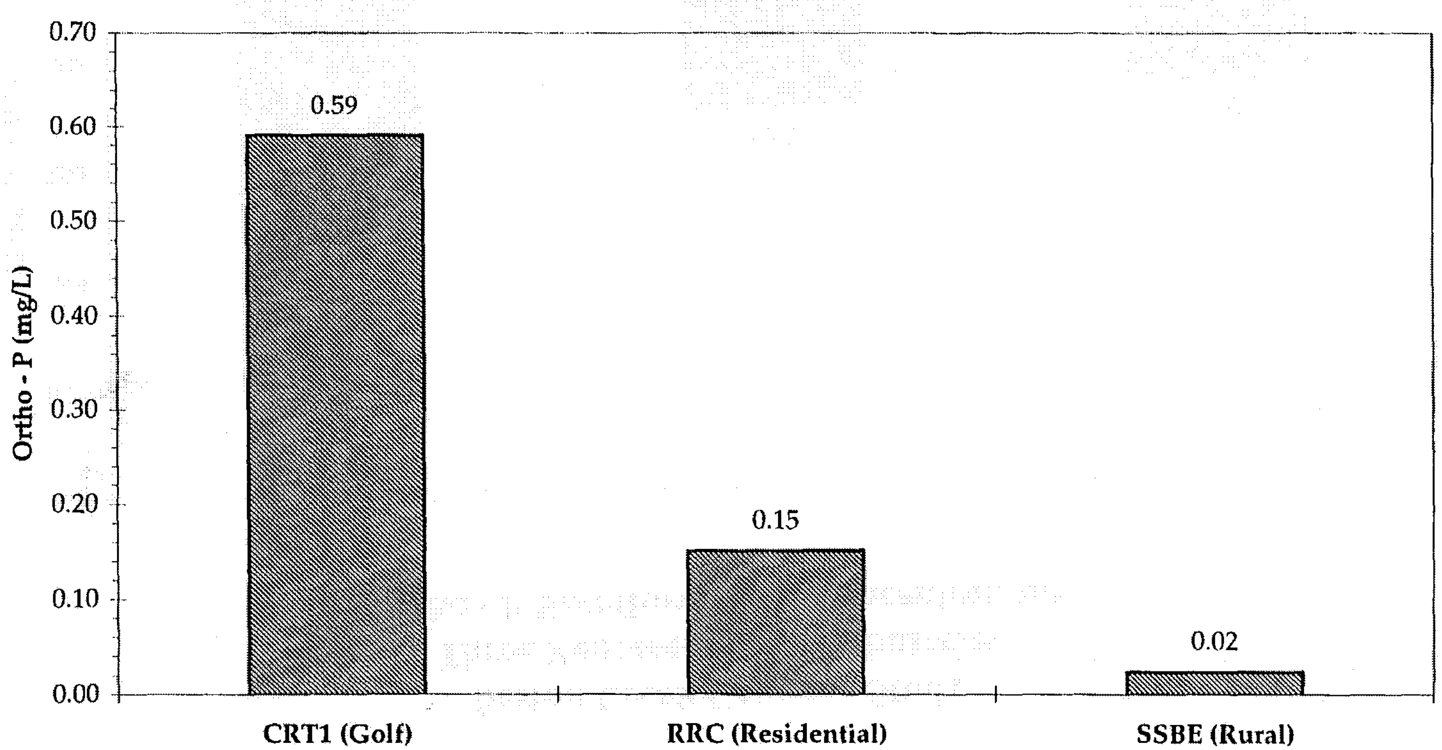
Barton Creek Canyons Study
Three Representative Tributaries
Ortho - P Baseflow Mean Concentrations



Source: COA / DUD Database 1993 - 1995

Figure 3.28

Barton Creek Canyons Study
Three Representative Tributaries
Ortho - P Stormflow Mean Concentrations



Source: COA / DUD Database 1993 - 1995

site (CRT1) than either the representative residential (RRC) or rural (SSBE) site (Figure 3.27). However, when analyzing all 38 sites, no significant difference in baseflow ortho-P was indicated among the three land uses. In addition, no significant differences were found in ortho-P concentrations between the two streams with different sized buffers.

During stormflow, ortho-P was statistically higher in the representative golf tributary (CRT1) than the rural tributary (SSBE) (Figure 3.28). Average ortho-P concentrations during storm events for golf, residential, and rural representative canyons were 0.59, 0.15, and 0.02 mg/L respectively. These differences are notable, because phosphorus runoff from golf courses during storm events may be an important factor in supporting dense filamentous algae blooms occurring in the vicinity of golf courses on the mainstem of Barton Creek. Flow regime, canopy cover, and other nutrients may also influence these events.

3.3.4.7 Nitrates

When examining baseflow at all 38 sites, nitrate-nitrogen concentrations were significantly different in the three principal land use categories. Median nitrate-nitrogen concentrations in golf course streams were highest at 0.63 mg/L, followed by residential and rural median concentrations of 0.20 and 0.05, respectively (Figure 3.29). Analysis of average and median baseflow nitrate values in the three representative streams also indicates significant differences between golf, residential, and rural tributaries (Figure 3.30), but this analysis places the residential stream (RRC) as the highest in nitrate-nitrogen, followed by the golf tributary (CRT1) and the rural tributary (SSBE). The results from all residential sites illustrate that this study's representative residential tributary (RRC) was in the high range of nitrate values when compared to other residential canyons.

Differences in nitrate concentrations are also illustrated by looking at the two residential canyons with different sized buffer zones. The canyon with the smallest buffer around the creek had significantly higher nitrate levels than the other canyon with a larger buffer (Figure 3.31). Furthermore, during baseflow, there was a significant difference in nitrate-nitrogen between rural canyons and all alternative wastewater land uses except residential on septic (Figure 3.32). Golf course effluent irrigated sites (at 0.63 mg/L) and residential on central system sites (at 0.60 mg/L) were highest and almost the same in median nitrate-nitrogen.

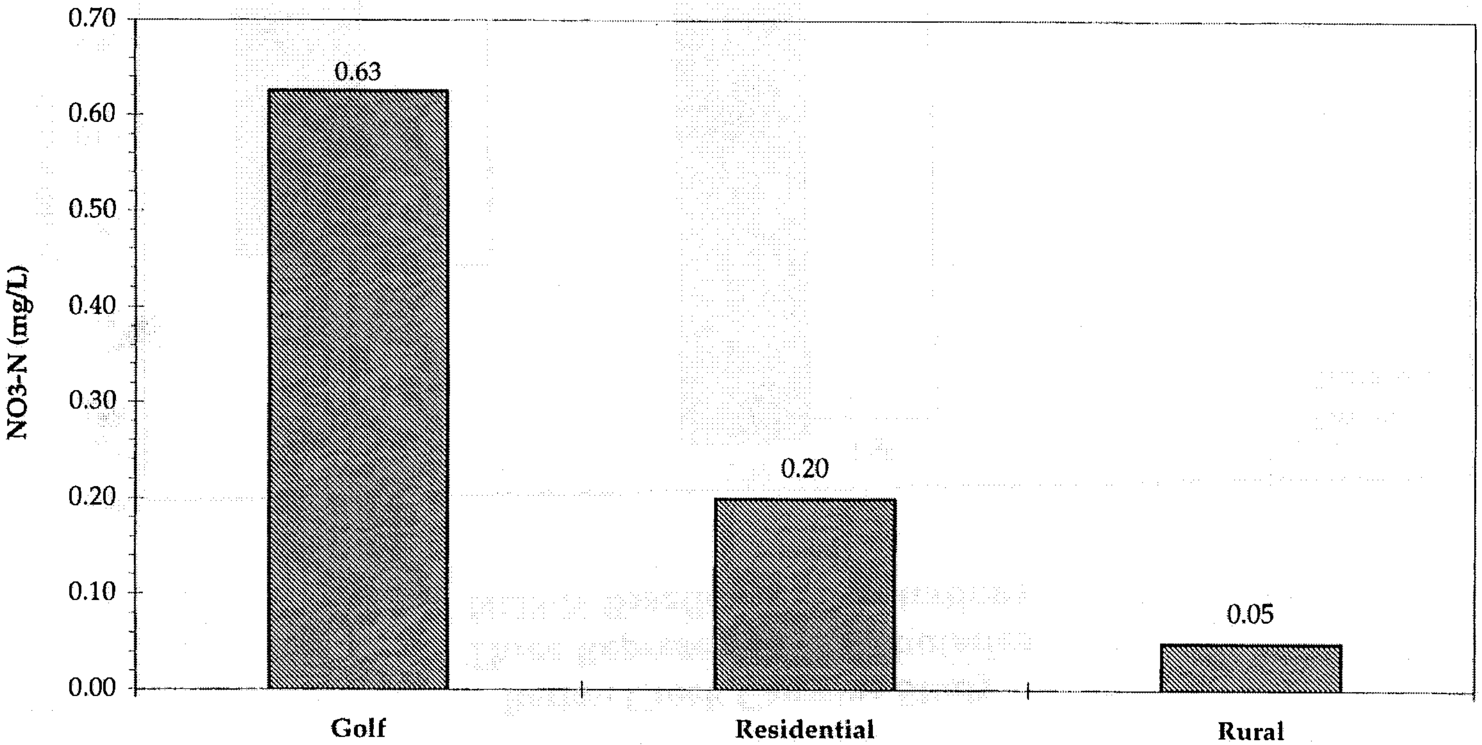
During storm events, there were also significant differences in nitrate-nitrogen levels among the representative golf, residential, and rural canyons. Figure 3.33 shows how nitrate levels were actually lower in the representative residential canyon (RRC) during storm events than during baseflow, even though nitrate levels rose somewhat in the representative golf tributary (CRT1) during these runoff conditions. The stormflow median nitrate-nitrogen concentration for representative golf, residential, and rural land use was 1.05, 0.6, and 0.14 mg/L respectively.

Given its importance in determining impacts to Barton Springs, nitrate-nitrogen may also be the most sensitive parameter that can be used to measure a development's impact on surface waters in the Barton Creek Watershed (Barrett, 1996). The nitrate parameter shows significant differences between all three principal land uses during both baseflow and stormflow conditions. Golf course land use creates the highest nitrate-nitrogen concentrations in surface waters in most analysis groupings; however, some individual residential streams, such as the representative residential stream (RRC), were higher in baseflow nitrates than the average golf course stream.

The results of this study indicate that irrigating native grasses with treated sewage effluent (commonly 15 to 20 mg/L NO_3) in residential areas had less impact on surface water quality than irrigating golf courses with the same resource (Metcalf and Eddy, 1991). This could be affected by differences in fertilization practices between golf course and residential land uses. However, the large native buffer zones required in residential canyons irrigating with effluent may be the most important factor influencing these results. This is due to both the filtration from irrigation field buffers and the dilution from cleaner baseflow infiltrating from the large canyon buffer. This hypothesis is further supported when examining the lower nitrate-nitrogen levels (0.13 vs. 1.25 mg/L) in the tributary with a larger sized buffer (Figure 3.31). Nitrate-nitrogen levels in surface waters of canyons on septic systems were not enhanced significantly over baseline concentrations found in rural canyon surface waters. Apparently, the larger lot sizes necessary in septic subdivisions and the creek buffer

Figure 3.29

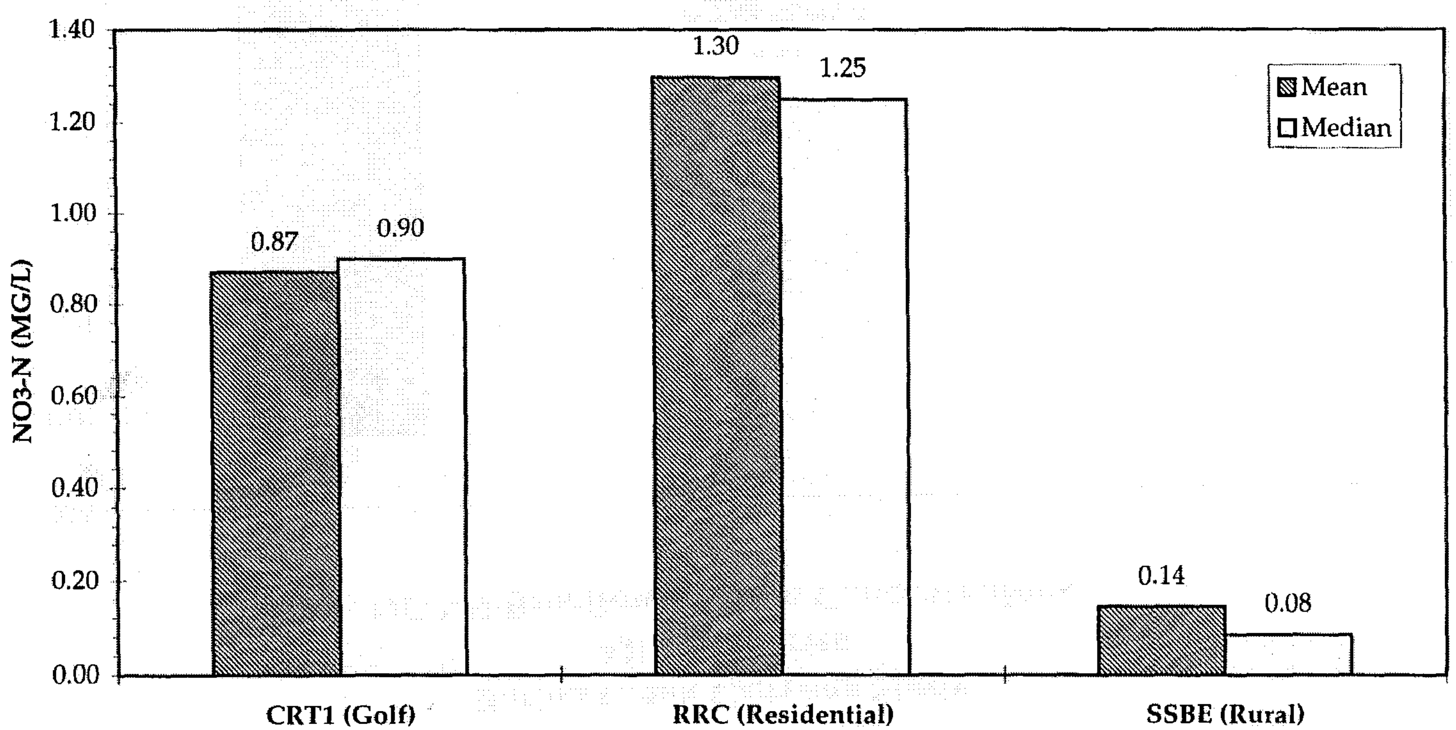
Barton Creek Canyons Study
All Tributaries
NO3-N Baseflow Median Concentrations



Source: COA/DUD Database 1993 - 1995

Figure 3.30

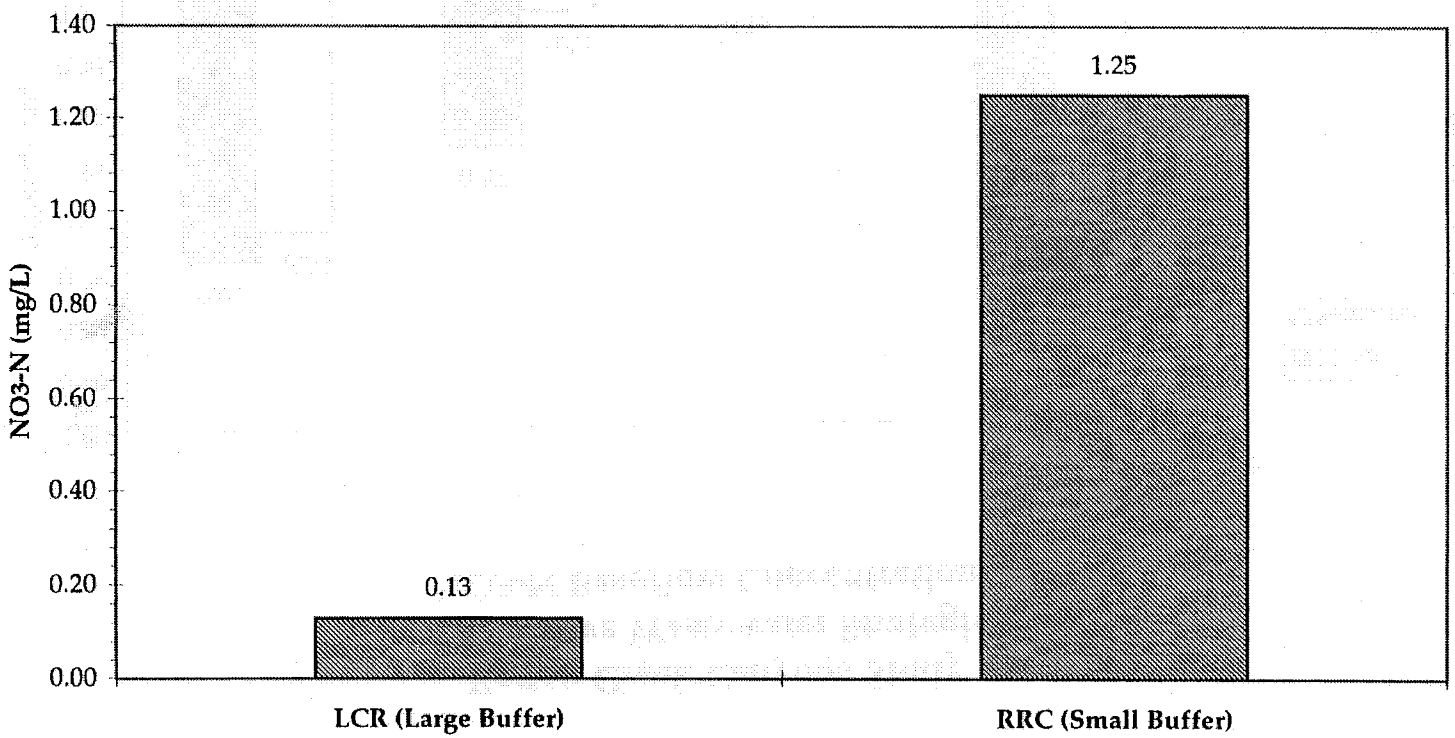
Barton Creek Canyons Study
Three Representative Tributaries
NO3-N Baseflow Concentrations



Source: COA / DUD Database 1993 - 1995

Figure 3.31

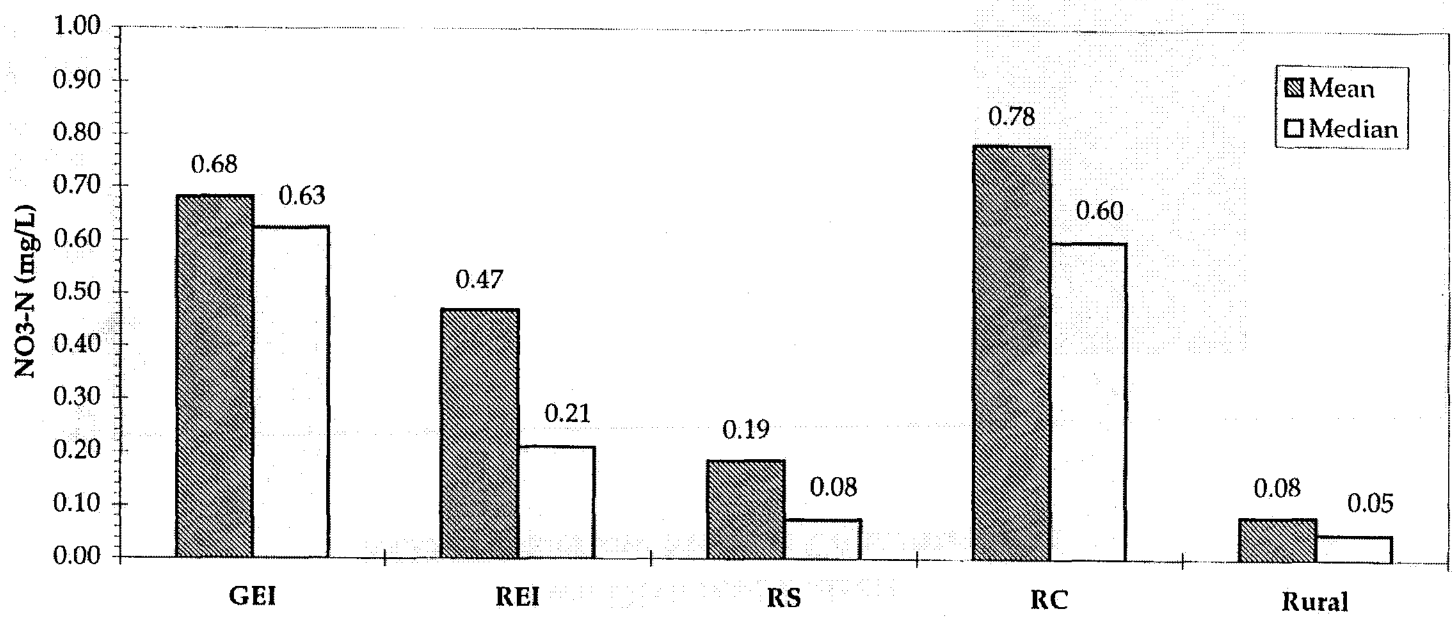
Barton Creek Canyons Study
Two Different Buffers
NO3-N Baseflow Median Concentrations



Source: COA / DUD Database 1993 - 1995

Figure 3.32

Barton Creek Canyons Study
Alternative Wastewater Strategies
NO3-N Baseflow Concentrations

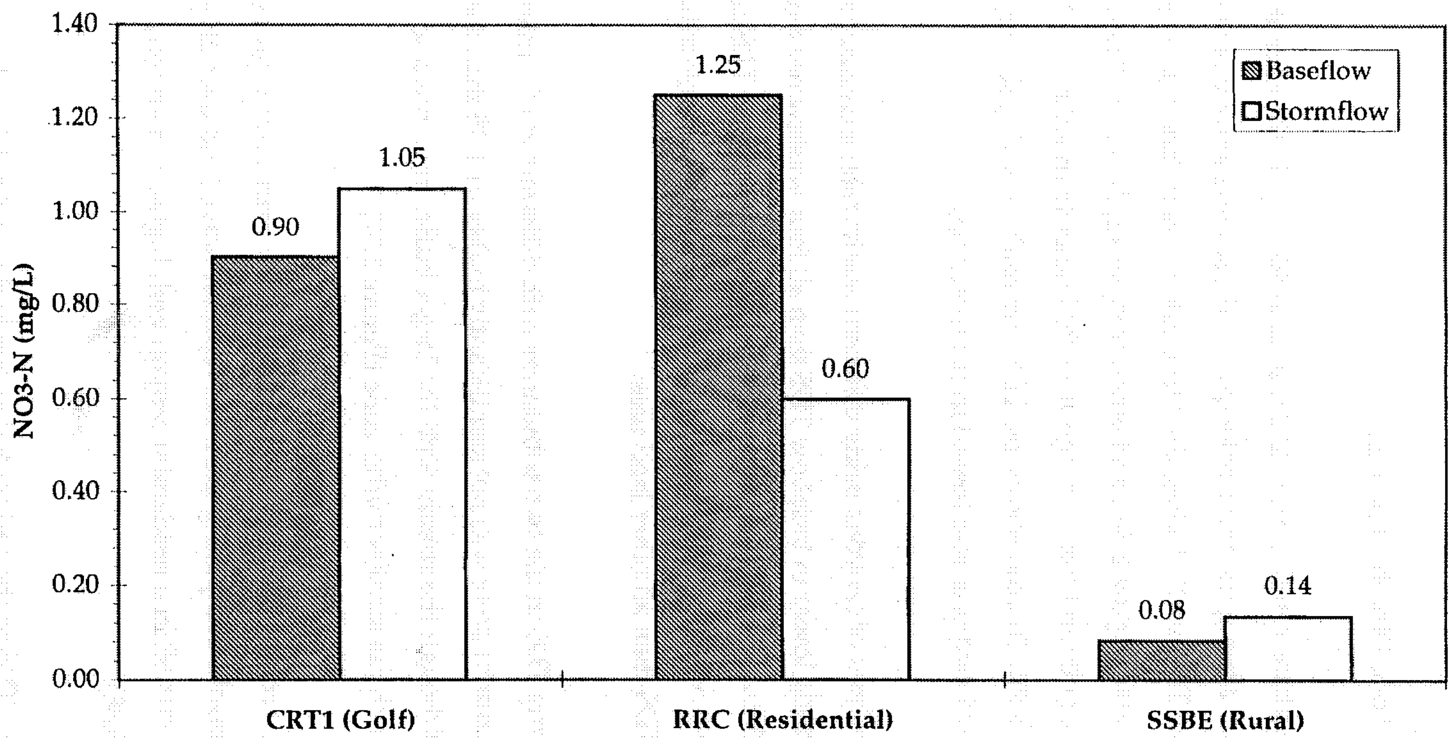


GEI - Golf Effluent Irrigated
REI - Residential Effluent Irrigated
RS - Residential Septic
RC - Residential Central
Rural - Undeveloped

Source: COA/ DUD Database 1993 - 1995

Figure 3.33

Barton Creek Canyons Study
Three Representative Tributaries
NO3-N Median Concentrations



Source: COA / DUD Database 1993 - 1995

zones required by the County Heath Department for septic fields are working to mitigate nitrate enhancement in surface waters.

3.3.4.8 Total Dissolved Solids

With medians ranging from 272 mg/L to 440 mg/L, significant differences in TDS were indicated among the three principal land uses in a variety of ways. When comparing baseflow TDS at all 38 sites, the three categories of land use were significantly different from one another (Figure 3.34), and when comparing baseflow TDS at the three representative canyons, golf land use was significantly higher than either residential or rural land uses (Figure 3.35). In both scenarios, TDS was highest with golf canyons, second highest in residential canyons, and lowest in rural canyons.

In an analysis of canyons using different wastewater treatment schemes , rural sites were significantly lower in baseflow TDS than all four wastewater treatment strategies (Figure 3.36). Effluent irrigated residential sites averaged higher TDS concentrations than streams on central or septic wastewater systems, and the golf course tributaries (GEI) averaged higher TDS than all other land uses.

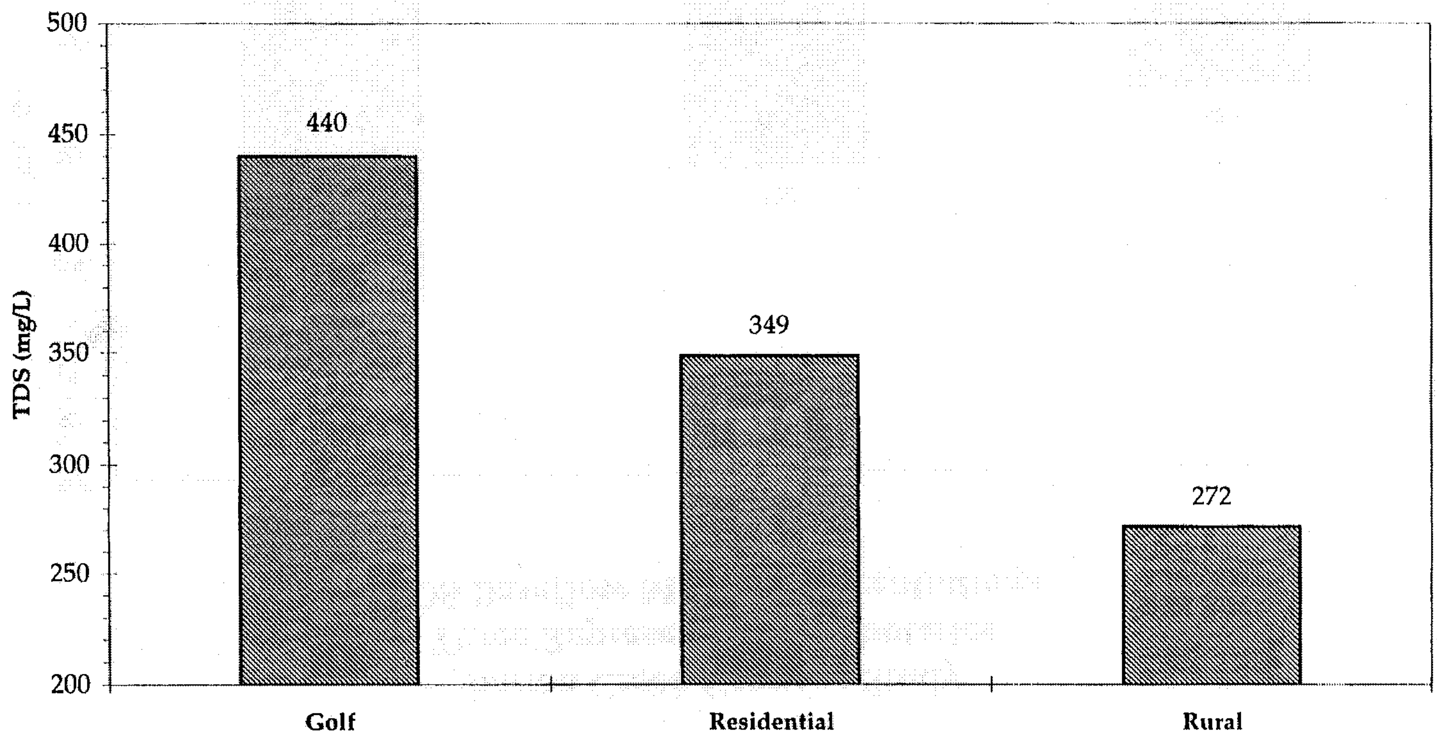
Comparing TDS in the two tributaries with different sized buffer zones, the stream with the smallest buffer zone was not significantly higher in TDS than the stream with the large buffer, although the stream with the larger buffer zone has a somewhat lower TDS than the stream with the smaller buffer zone (Figure 3.37).

During stormflow, TDS is typically diluted by storm water runoff (Hynes, 1970). The canyon results comparing the three representative land uses illustrate how much more runoff occurred in a residential canyon with higher impervious cover than a rural canyon (Figure 3.38).

Stormflow TDS in the residential watershed was significantly lower than TDS in rural watershed. While median TDS dropped substantially from baseflow concentrations at the

Figure 3.34

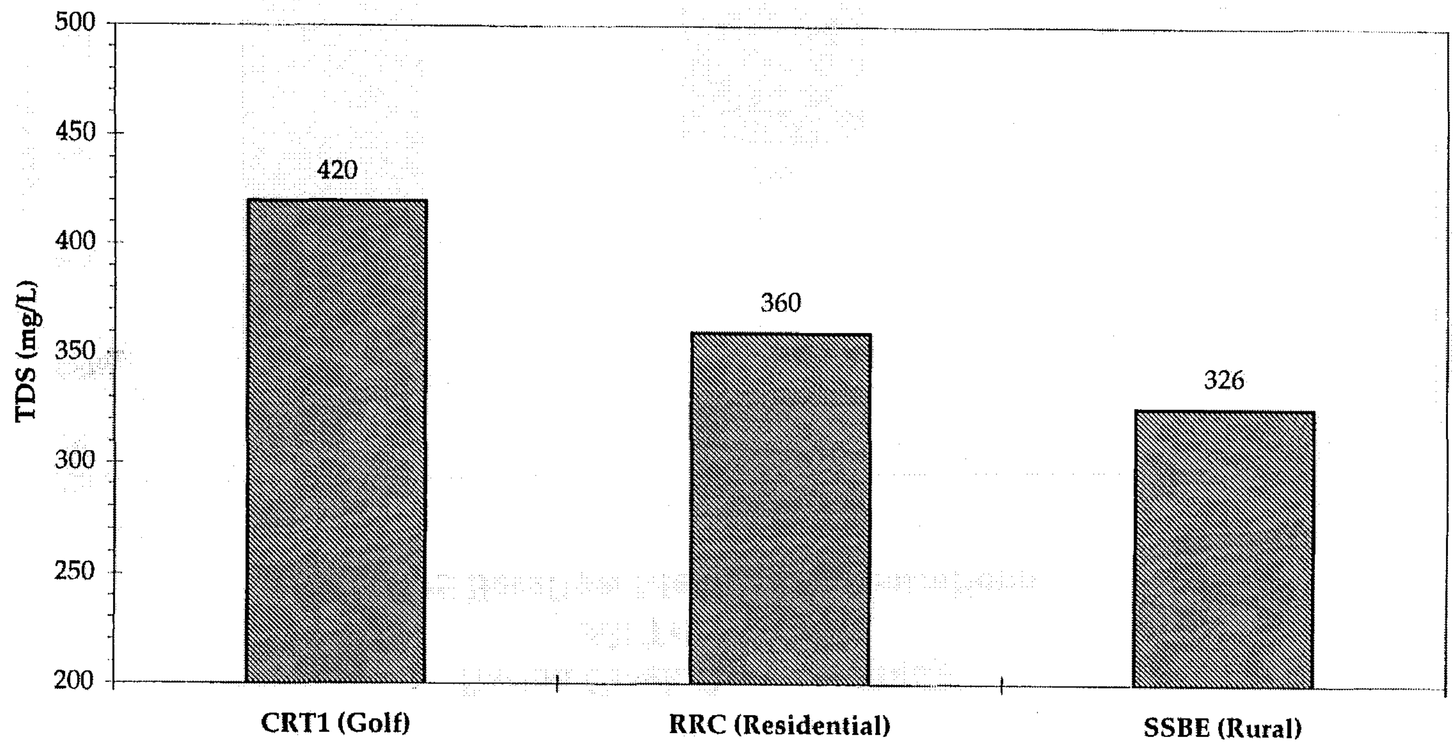
Barton Creek Canyons Study
All Tributaries
TDS Baseflow Median Concentrations



Source: COA/DUD Database 1993 - 1995

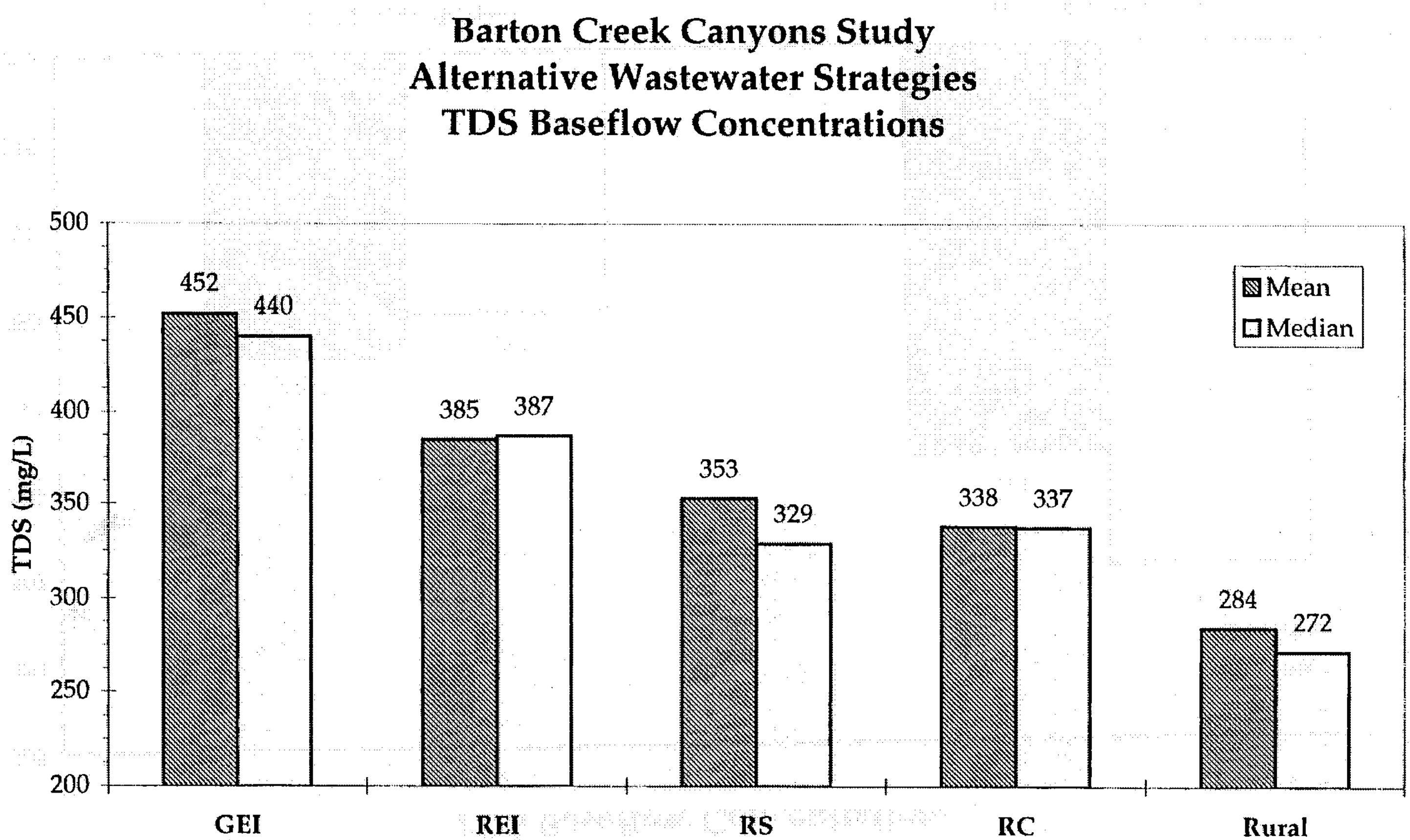
Figure 3.35

Barton Creek Canyons Study
Three Representative Tributaries
TDS Baseflow Median Concentrations



Source: COA / DUD Database 1993 - 1995

Figure 3.36

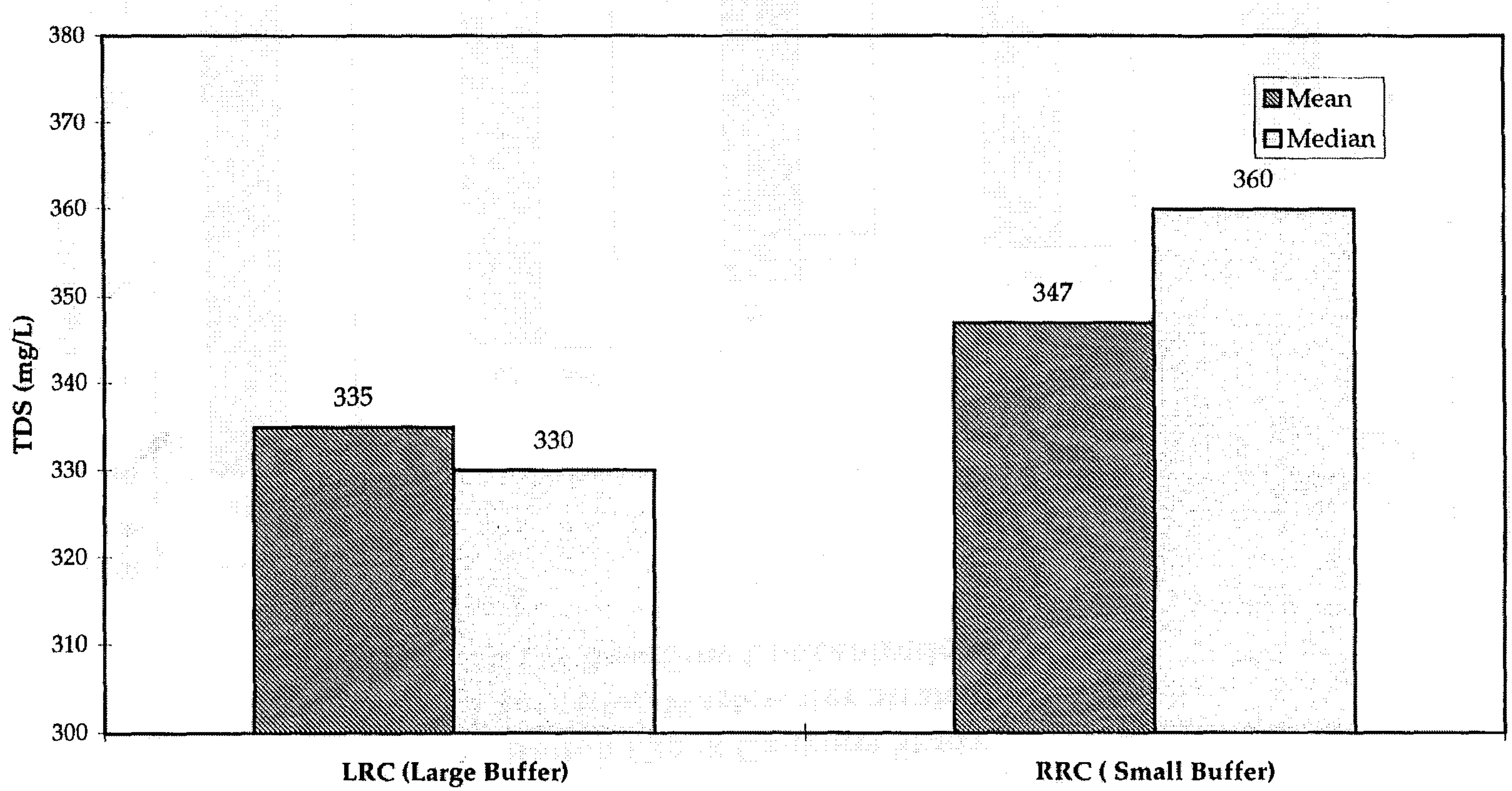


GEI - Golf Effluent Irrigated
REI - Residential Effluent Irrigated
RS - Residential Septic
RC - Residential Central
Rural - Undeveloped

Source: COA/ DUD Database 1993 - 1995

Figure 3.37

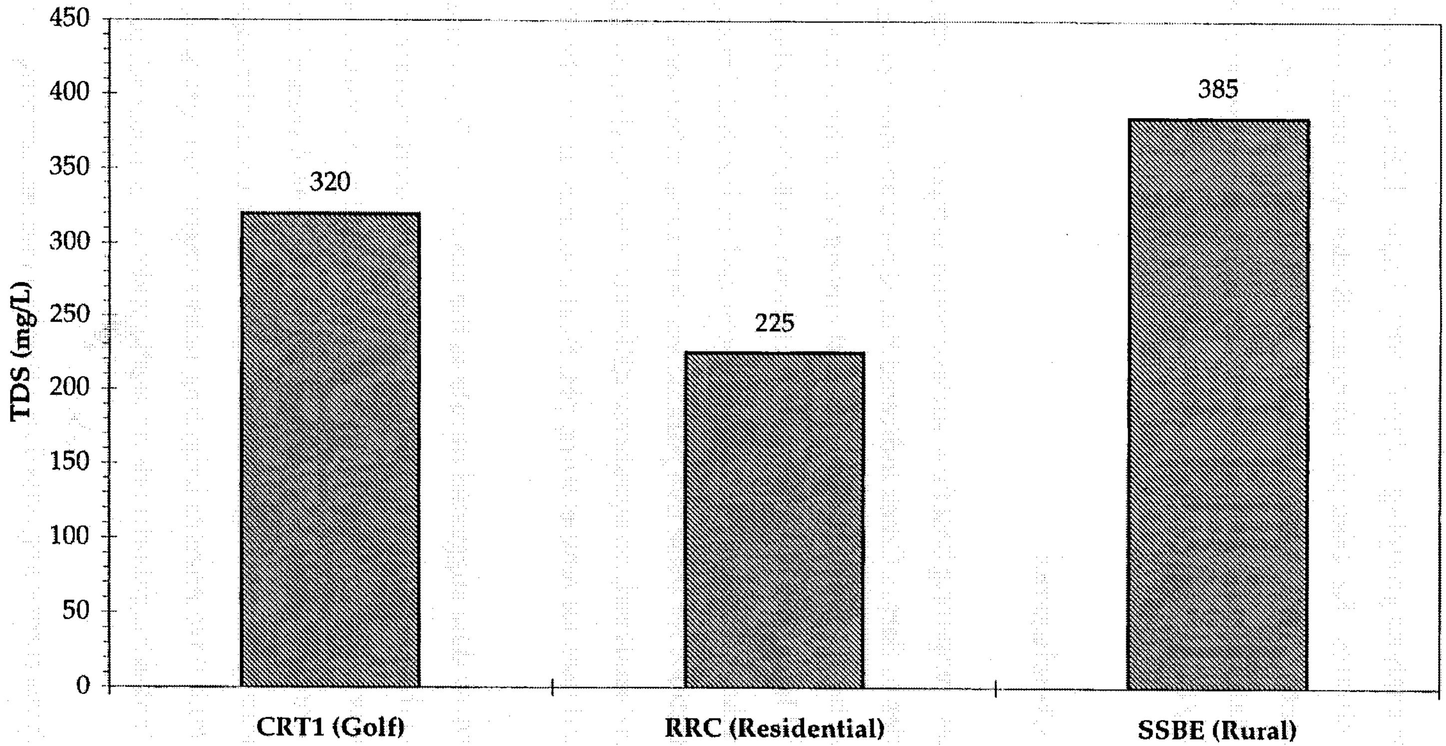
Barton Creek Canyons Study
Two Different Buffers
TDS Baseflow Concentrations



Source: COA/DUD Database 1993-1995

Figure 3.38

Barton Creek Canyons Study
Three Representative Tributaries
TDS Stormflow Median Concentrations



Source: COA / DUD Database 1993 - 1995

representative golf and residential sites during storm events, median storm TDS unexpectedly increased at the representative rural site (Figures 3.35 and 3.38).

In most analysis groupings, significantly higher TDS was accompanied by significantly higher nitrates. For example, when all 38 sites were analyzed, golf course land use had significantly higher nitrate-nitrogen and TDS (0.63 mg/L and 440 mg/L respectively), as did residential land use (0.20 mg/L and 349 mg/L respectively) compared to rural land use (0.05 mg/L and 272 mg/L respectively).

3.3.5 Conclusions

Analyses comparing baseflow surface water samples intermittently collected at 38 sites on tributaries to Barton Creek indicated that significant differences in nitrate, ammonia, TDS, TSS, and turbidity concentrations exist among watersheds draining golf courses, residential, and rural land uses. Golf course tributaries usually had higher constituent concentrations than residential tributaries, and both golf and residential drainages had substantially higher concentrations for these five parameters than rural tributaries. However, when these 38 sites were analyzed, no significant differences were indicated during baseflow among the three land uses for temperature, pH, fecal coliform, and ortho-P.

- Baseflow data suggested nitrate as the most variable parameter in the Barton Creek watershed canyon data. A comparison of tributaries characterized by alternative wastewater treatment strategies revealed that golf course watersheds using sewage effluent irrigation and fully developed residential watersheds on central wastewater systems generated significantly higher nitrate concentrations in their surface waters than residential watersheds irrigating native vegetation/grass areas with sewage effluent, residential neighborhoods on septic systems, or undeveloped rural watersheds.

- Analyses comparing baseflow samples collected contemporaneously from three selected tributaries representing golf course, residential, and rural land use indicated significant differences in pH, nitrate, TDS, ortho-P, fecal coliform, and turbidity concentrations. Although, in this analysis scheme, the golf course stream was highest in ortho phosphorus, TDS, and turbidity; the residential site was highest in nitrates, fecal coliform, and pH. No significant differences were observed between these three representative tributaries in TSS and ammonia values.

When water samples were collected simultaneously during storm events from the three representative tributaries, the golf course site was significantly higher than the other land uses in nitrates and ortho-P, while the residential site was significantly higher in pH and lower in TDS than the other two land uses. The residential site's lower TDS illustrated the heavier storm runoff experienced in land uses with more impervious cover. The higher nutrient concentrations, especially phosphorus, in the golf course runoff may play a role in increased algae coverage observed and measured on the mainstem of Barton Creek, downstream of the golf courses.

- Baseflow water quality samples collected contemporaneously from two adjacent residential canyons indicated that the size of the undeveloped buffer zone around a stream may be related to water quality. Median nitrate concentrations in these two canyons indicated that water quality may improve as buffer zone size increases. Furthermore, higher pH values were mitigated by larger buffer zones. The sample size associated with this analysis renders the conclusions preliminary; they are, however supported by national data (Schueler, 1995b). Besides pollutant removal, the benefits of buffer zones are numerous (Appendix D), and include decreases in impervious cover, effective flood control, and protection from streambank erosion.

- In review of the canyon study data analyses, it was determined that no one distribution fit the data sets or groupings used. In addition, the number of values below detection limits were significant in some parameters. For these reasons, non-parametric methods of statistical analysis were found to be more appropriate than those requiring normality or transforms to obtain normality.

- In summary, when compared to canyons representing rural land use, some form of statistically significant water quality degradation can be documented for tributaries representing any of the developed land use categories. With few exceptions, golf course land use has the greatest impact on surface water quality during baseflow and stormflow, and the most pristine waters are always associated with rural land use. Residential canyons irrigating native grass areas with treated sewage effluent have less impact on surface water quality than irrigated golf courses using the same resource. In addition, from the data available to date, it appears that buffer zones mitigate impacts to water quality in residential areas on central sewage systems, and buffers or larger lot sizes associated with residential areas using septic systems may function to keep excess nutrients and bacteria from reaching surface waters.

3.3.6 Recommendations For Future Monitoring

City staff have developed a large data base of water chemistry assessments in a number of tributaries to Barton Creek which have been characterized according to land use. This report has documented significant differences in water quality between rural streams and various types of developed tributaries. Findings of this report also support the results of studies nationwide that large undeveloped buffer zones around creeks protect developed streams from water quality impacts. Most of the study streams in this report are characterized in general terms, and work needs to be done to detail and compare water quality differences among other watershed attributes such as percent impervious cover, buffer zone sizes, presence of water quality controls, and other ordinance driven characteristics. This is especially important in determining the mitigating effects of different buffer size on golf course pollutant loadings. Due to the gradation of vegetated cover near golf course waterways it was uncertain where to delineate the buffer zone for this study.

It is recommended that the City continue to collect water quality information in as many tributaries to Barton Creek as possible on a monthly basis to measure the effectiveness of current City ordinances, water quality protection zones, and land management practices in fully developed areas. Tributaries which are currently undeveloped, but planned for development, should be top priority and monitored regularly to determine what impacts, if any, are associated with particular development practices and regulatory policies.

Installation of automated monitoring stations in these tributaries will allow detailed comparisons of event mean concentrations, hydrographs, and pollutographs.

3.4 BARTON CREEK SEDIMENT DATA REPORT

3.4.1 Introduction

Traditionally, water quality has been assessed by studying the concentrations of dissolved constituents in the water column. However, the study of sediments that accumulate on the bottom of a water body is typically performed to supplement water quality data and to provide a better historical representation of contamination. The utility of sediments as an environmental indicator is mainly due to 1) the sorption of heavy metals and complex organic pollutants to particulate organic matter in the sediments, and 2) the less transitory nature of the sediments in comparison to the given mass of water in lotic systems. Because sediments serve as a reservoir for toxic constituents and provide an excellent historical record, their study has been important in assessing the short and long term effects of pollution and urbanization on local waterways. In addition, many harmful components bioaccumulate in the tissue of benthic macroinvertebrates that occupy or depend on the sedimentary environment for their various life functions. Sediments can also be obtained in intermittent streams, which are common in Central Texas, and are not dependent on habitat type for collection. These monitoring benefits led to studies conducted by the City of Austin's Environmental Resource Management Division (ERM) of the sediments along Barton Creek.

ERM collected samples from sites along Barton Creek between 1991 and 1995 (Plate 4). Table 3.12 represents these sediment sites with reference to their location on Barton Creek by river kilometer.

These samples were gathered by five different project teams, each attempting to detect trends in the accumulation of heavy metals, organic pesticides and other organic constituents (Figure 3.39). Although the basic goal was the same, every project team had a more specific purpose. The *Bioassessment* Project was funded by State Senate Bill 818, the Clean Rivers Act, to run from May 1993 to August 1996. The purpose of this pilot project was to evaluate the impact of nonpoint source pollution on Barton and Onion creeks using biological indicators and EPA rapid bioassessment protocols. Sediments at six selected sites on Barton Creek were sampled once to establish background conditions during the study. The *Environmental Integrity Index (EII)* study was developed by ERM as a monitoring and evaluation tool to compare and rank Austin creeks. Water chemistry, biological, physical, recreational and sediment collection protocols are used to assess the quality of the urban and non-urban study creeks for use in prioritization in the Drainage Utility Masterplan. This report includes sediment data from the first two sampling events. The ***Contaminated Sediment Grant*** is a three year EPA 319 grant, started in 1994, that is designed to study sediment removal by Best Management Practices (BMPs). This project sampled sediment at two BMP sites that appear in this data set. The ***Town Lake Sediment Study*** is an ongoing project targeting the effects of contributing creeks to the Town Lake basin. Three Barton Creek sites were sampled once during this study, one site far upstream, one midstream and one just above Barton Springs Pool. The remaining data sets are from various sediment samples collected over the years that were not part of a particular study or project. They were one-time collections that evaluated the sediment quality of a specific site at a specific time according to City of Austin assessment needs. This report serves to consolidate and compare Barton Creek sediment data from all available sources.

3.4.2 Description of Study

3.4.2.1 Study Area

The fluvial processes of Barton Creek create a pool and riffle morphology in which the riffles are characterized by rapid flow, and shallow depth, while the pools are deeper, have gentle gradients and low flow velocities. As a result, riffles are composed mainly of cobble, gravel and coarse-grain sand, whereas pools consist of bedrock or a cobble-boulder combination with a fine sediment cover approximately 2 to 5 mm thick.

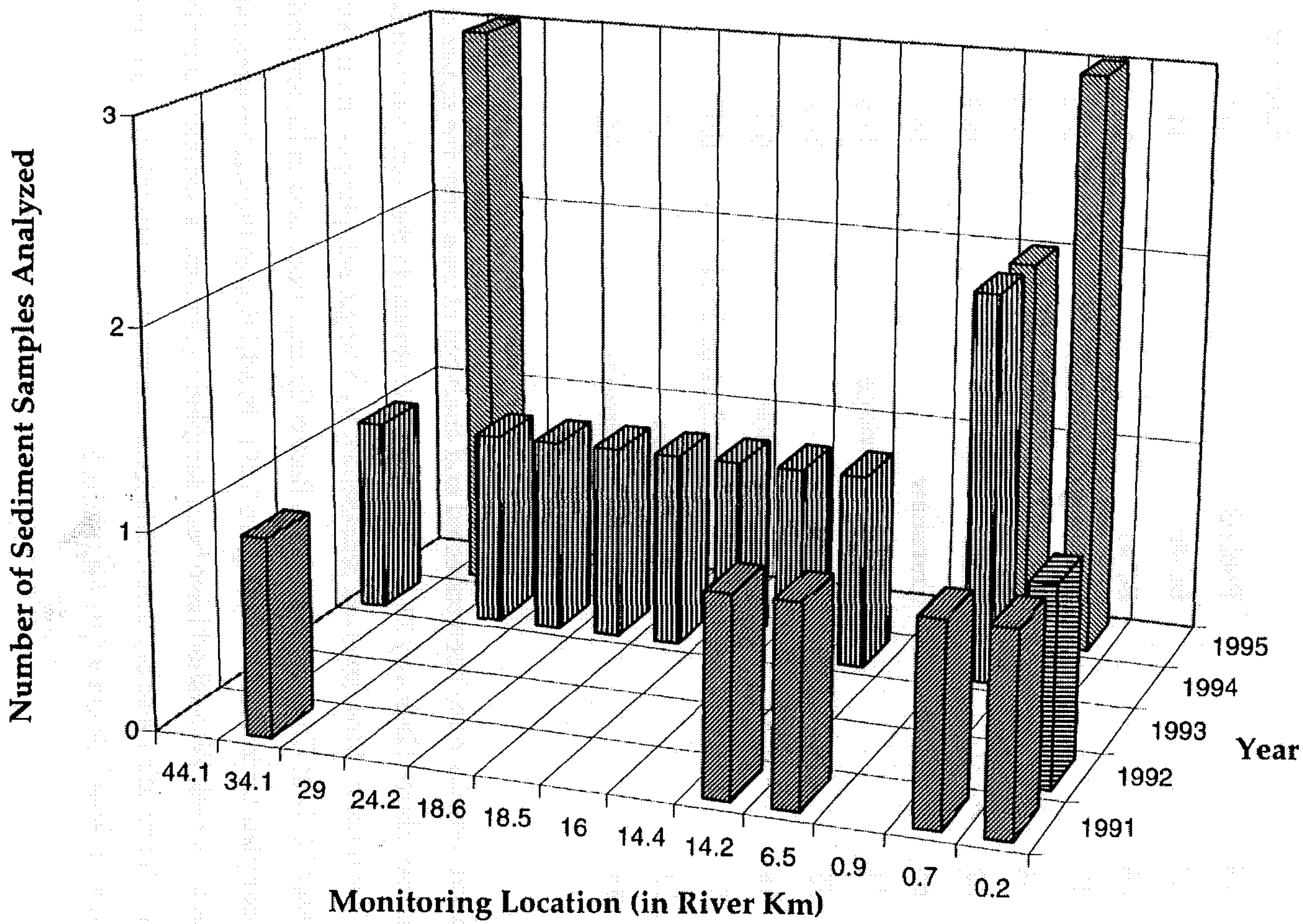
Table 3.12 Sediment Monitoring Locations

Site Number	Site Name	River Kilometer
15	Pool #3	44.1
23	BC #0	34.1
34	BC #1	29
42	Hebbingston Hollow	24.2
51	Rob Roy	18.6
52	Fazio	18.5
63	Crenshaw	16
74	Lost Creek Bridge	14.4
75	BC #10	14.2
89	Campbell's Hole	6.5
91	Above Barton Springs Pool	0.9
92	Barton Springs	0.7
98	Barton Creek mouth	0.2

Sediment samples have been collected and analyzed at sites from the upper section of the watershed, above Highway 71, all the way downstream to the confluence of Barton Creek with Town Lake. Most sites are represented by a single sampling event; however, sites at Highway 71, Lost Creek Bridge, above Barton Springs Pool, and in Barton Springs Pool have been sampled up to four times (Figure 3.39). In addition to the stream sites, inlet filters in the Barton Creek Watershed have been sampled to determine sediment quality of stormwater runoff (Sites 87,91,96). Site locations referenced in this section are shown on Plate 4 and cross-referenced in Appendix F.

Figure 3.39

Barton Creek Sediment Sampling Frequency



Source: COA/DUD Database 1991-1995

3.4.2.2 Sampling and Analysis Methods

All equipment used by ERM for sediment sampling was prepared using a method described by the TNRCC (Surface Water Quality Monitoring Procedures Manual, 1994). The samples analyzed were composited from six grab samples collected using a petite ponar dredge and/or a Teflon scoop. At monitoring sites where the sediment deposits were thick enough, the ponar dredge was used exclusively. However, at most of the upstream monitoring sites, accumulated sediment was sparse and thinly deposited, requiring the use of a Teflon scoop to augment these collections. Because sediment was sparse in many areas, percent fines in samples may not accurately represent the total percent fines at each site. Anoxic sediments were avoided if encountered. The grab samples were composited in a large glass bowl and mixed with a Teflon scoop. The composite sample was then transferred into glass sample jars with Teflon lids and stored at 4 ° C for transportation to the lab for analysis. The resulting sediment data are bulk chemical analysis of the submitted sample. All lab analysis is reported in dry weight.

Over the course of the sampling, sediments were analyzed at two laboratories, LCRA Environmental Lab and Inchcape Lab (NDRC). Sometimes these labs were used for different sites and other times they were used for the same sampling event in order to generate duplicate site data. Detection limits differed because of the nature of sediment analysis, and at times the laboratory detection limits were higher than the expected concentrations at a given site. The list of analyzed parameters also varies throughout this period because the data originated from many studies carried out by different groups for different evaluation purposes. Certain groups of standard sediment constituents were routinely analyzed by both labs and will be discussed in the results section of this report.

All laboratory quality control was carried out by the selected laboratory's according to standard EPA quality control procedures for analysis of sediment/soil constituents. Results reported here have been quality verified according to each laboratory's quality control plan. The data were managed in the City of Austin's water quality database and manually verified after data entry or transfer. Duplicate samples were sent to two different labs for quality assurance purposes at three of the sites in this data set. Since this is an assortment of studies and individual samples, a comprehensive quality assurance plan was not possible. Although quality assurance was approached differently in each study, the certified laboratories involved used consistent QA methods.

3.4.2.3 Data Analysis Methods

To compensate for data source variability and allow more consistency in the data set, analysis of certain parameters was emphasized. Parameter selection was based on their availability in the data set and their importance in aquatic environments. The parameters were then grouped for simplification. Table 3.13 offers an overview of the parameter groupings followed by a more detailed description of the reasoning behind each group's selection.

The evaluation of heavy metals was necessary because elevated levels are attributed to nonpoint source pollution and can be toxic to aquatic organisms. Although low metal concentrations occur naturally in the environment and are essential as micronutrients for an organism's growth and metabolism, the use of fertilizers, herbicides, gasoline, motor oil, and other metal-containing manufactured goods can cause metal concentrations to increase to harmful levels. The potential of metals to become toxic is dependent upon the availability of these constituents to organisms in the environment. As a result, assessment of sediment metal concentrations was enhanced by examining the factors which influence metal bioavailability and toxicity, such as grain size, percent dry weight, and acid volatile sulfide concentrations.

Polycyclic aromatic hydrocarbons (PAH's) were analyzed because of their tendency to be characterized as carcinogens or mutagens. These benzene-based hydrocarbons originate from both natural and man-made sources; however, the major input of PAHs into the environment is associated with storm water run-off containing motor oil, gasoline, and engine emissions. Organic constituents adsorb quickly to particulate matter in receiving waters due to the formation of either a chemical or physical bond between the organic compound and the sediment (Kahn, 1978). Because of their wide dissemination, they are among the most frequently observed organic pollutants in runoff. Pesticides are detected less often than PAHs in water or sediment samples in the Austin area. However, they continue to be monitored because of their extreme toxicity and tendency to bioaccumulate.

Nutrients, in conjunction with several other general chemical and biological variables, were also routinely measured in this data set in order to quantify background conditions and to further collaborate metabolic processes in sediments. Although their analysis can sometimes be appropriate and useful, most results are not discussed in depth here because no levels of concern, distinct trends or evident connections to current environmental conditions were determined.

The evaluation and analysis of sediment quality are difficult due to a lack of state or federally adopted criteria. Researchers commonly disagree on factors that influence the biological effects of contaminants in sediment. As a result, agencies have developed their own methods for setting guidelines or screening values to aid in interpreting sediment data. Two evaluation criteria approaches were selected for use in this report: the National Oceanic Atmospheric Administration's (NOAA) informal effects range-low (ER-L) and effects range-medium (ER-M) guideline, and TNRCC's 85th percentile.

NOAA developed the ER-L (lower 10th percentile) and ER-M (median value) under the National Status and Trends (NS&T) Program, as a guideline to aid in the evaluation of collected sediment data (Long, E. R. 1991). The ER-L and ER-M are biological effect levels objectively selected from primarily estuarine sediment chemistry data which showed some degree of toxicity. The potential for biological effect to occur increases as the chemical parameters from a sediment sample surpass the ER-L and ER-M levels. Effects could occur when levels exceed the ER-L and values above the ER-M indicate that effects are probable. These values should be used as informal ranking tools, not as strict criteria.

The TNRCC has developed screening levels for metals and toxicants in sediment based on its database of observed values for specific metals and organic substances throughout Texas (305b, TNRCC. 1996). Twelve metals and 25 organic substances were identified and assigned criteria values based on the 85^{th} percentile of their state-wide database.

Table 3.13

Sediment Variables by Group

Metals (mg/kg)	Polycyclic Aromatic Hydrocarbons (ug/kg)	Pesticides/ Herbicides (ug/kg)	Nutrients (mg/kg)	Grain Size(%)	Miscellaneous
Arsenic	Acenapthene	Aldrin	Ammonia	Gravel	Total Organic Carbon
Cadmium	Acenapthylene	Chlordane	Nitrate/Nitrite	Sand	Acid Volatile Sulfides
Chromium	Anthracene	DDD	Ortho-phosphorus	Silt	Chemical Oxygen Demand
Copper	Benzo(a) anthracene	DDE	Phosphorus	Clay	Percent Dry Weight
Lead	Benzo(a) pyrene	DDT	TKN		Total Petroleum Hydrocarbons
Mercury	Benzo(b) fluoranthene	Delta-BHC			Volatile Solids
Zinc	Benzo(g,h,i) perylene	Endrin			
	Benzo(k) fluoranthene	Heptachlor			
	Chrysene	Heptachlor Epoxide			
	Dibenz(a,h) anthracene	Malathion			
	Fluorene	Parathion			
	Fluoranthene	PCBs			
	Indeno(1,2,3) pyrene				
	Napthalene				
	Phenanthrene				
	Pyrene				

Source: COA database, 1991-1995

Any value found which exceeds this criterion would be higher than 85 percent of the values assessed in Texas.

3.4.3 Results

Metals:

Five trace metals, arsenic, copper, cadmium, lead, and zinc were evaluated because they were routinely analyzed at all monitoring sites. Table 3.14 indicates that only three metal concentrations exceeded either of the methodological guidelines referred to above. Two of the three values of concern, cadmium at 23.40 mg/kg and arsenic at 17.00 mg/kg, were collected in one sample at site 15, which is a relatively undeveloped site. Both of these values exceeded the TNRCC 85th percentiles of 1.140 mg/kg and 6.600 mg/kg respectively. The cadmium value exceeded the ER-M value of 9.00 mg/kg. An arsenic value of 7.02 mg/kg was found in one sample at site 51; this is above the TNRCC 85th percentile but not the NOAA ER-L of 33.00 mg/kg. A tributary above this site draining a residential subdivision could be the source of this value. Although the remainder of the metal data fell below the national and state standards, copper, lead and zinc levels showed increases at the downstream sites (Figure 3.40). Because of the relationship between grain size and metal adsorption rate, these higher levels may be attributed to the greater percentage of fine grain material found at the farthest downstream sites as indicated in Figure 3.41. These elevated concentrations may also be the result of the accumulation of sediment constituents from the entire watershed or from localized runoff of developed land uses in the immediate urban areas around Barton Springs.

Polycyclic Aromatic Hydrocarbons:

Figure 3.42 shows all of the PAH levels that were found above detection limit in the Barton Creek watershed in collections since 1991. (See Appendix for a complete list of PAH values.) As is evident from the graph, there were no values above the detection limit at the upstream or midstream sites; PAH's were detected only at the two locations in the Barton Springs area (sites 91 and 92) and at the two inlet filter drainage structure sites (sites 87 and 96). These levels were very high, exceeding the NOAA ER-L in every case and the ER-M in most samples. In fact, five sample sets exceeded nine or 10 ER-M criteria values by as much as

23,147 ug/kg, as was the case at the site immediately above Barton Springs Pool (site 91) on November 21, 1994. The TNRCC 85th percentiles for most PAHs (750 ug/kg) were exceeded dramatically by the same five sample sets collected in and above Barton Springs (Figure 3.42). These high PAH values in and around Barton Springs also greatly exceeded values from samples collected from the inlet filter sites which are designed to trap and concentrate polluted stormwater runoff from roads and parking lots.

Pesticides

Although many organic pesticides were analyzed for, very few were found in detectable concentrations. The only sample set with levels above the detection limits occurred at the site immediately above Barton Springs Pool on November 21, 1994. Table 3.15, below, lists all of the detected pesticides from this sample. The pesticide levels from this sample are much higher than the TNRCC 85th percentiles (TNRCC 305b. 1997). The values exceeded the 85th percentile by as little as 4.57 ug/kg with Heptachlor Epoxide and as much as 743 ug/kg with DDD. In addition, many of the pesticides detected were at higher concentrations than any other water or sediment sample collected in the watershed by ERM in past years. NOAA ER-L/ER-M criteria were incomplete for this data set. Since this is one sample point, these data can only be used as an indicator of a possible problem.

Total Petroleum Hydrocarbons

The values for Total Petroleum Hydrocarbons (TPH) in the Barton Creek Watershed fluctuated greatly from upstream to downstream, ranging from non-detectable levels at Barton Springs (site 92) and site numbers 15 and 79 to 622 mg/kg at site 51 which is located in a residential development drainage area. In comparison, the two highest values of 5240 and 5500 mg/kg, were detected in sediments collected from a BMP inlet filter in the watershed. This BMP site collects runoff from road and parking lot surfaces which are major accumulation areas for petroleum products. ERM data indicate that although the BMP values were average for this area, the value of 622 mg/kg was relatively high for a residential drainage area. Similar values have been found at the mouths of other urban creeks, but levels such as this are rare for upper and midstream sites. TNRCC and NOAA screening levels were not available for TPH.

Table 3.14

Tabulated Metal Concentrations

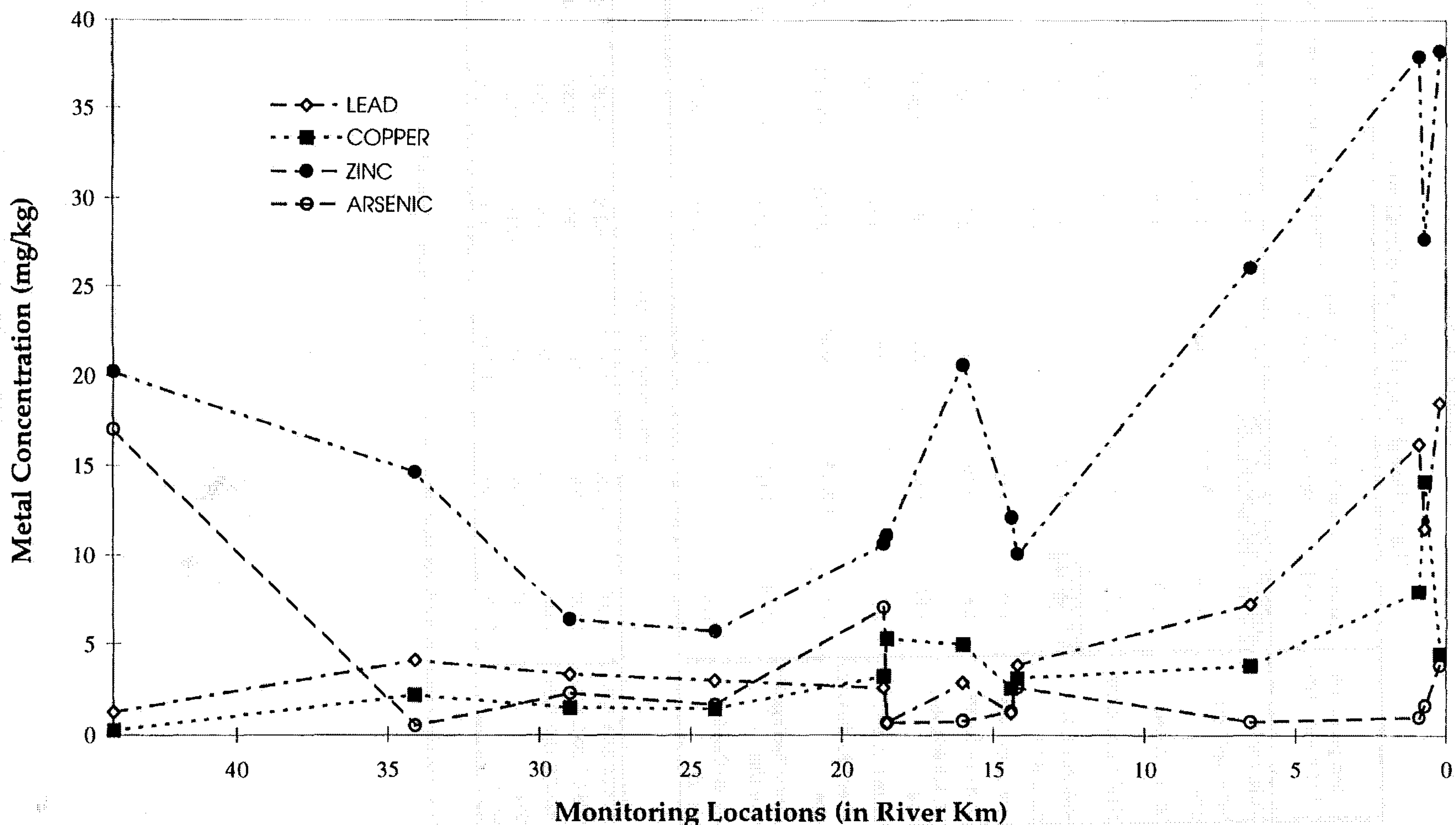
Sample Site & Collection Dates	Arsenic mg/kg	Cadmium mg/kg	Chromium mg/kg	Copper mg/kg	Lead mg/kg	Zinc mg/kg
Shield 5/94	17.00	23.40	18.00	<0.5	<2.5	20.20
BC #0 4/95 thru 7/95	0.52 (2)	0.52 (3)	3.36	2.21 (4)	4.12 (4)	14.63 (4)
BC #1 6/27/94	2.30	0.38	.	1.50	3.34	6.37
Hebbingston 6/94	1.65	0.44	.	1.45	3.00	5.70
Rob Roy 6/94	7.02	<0.27	.	3.24	2.60	10.62
Fazio 6/94	<1.3	<0.27	.	5.28	<1.3	11.07
Crenshaw 6/94	0.76	0.50	.	4.98	2.88	20.59
Lost Creek 5/94	1.30	<0.25	<0.35	2.60	<2.5	12.10
BC #10 9/91 thru 6/94	2.63	0.43	2.50	3.14 (2)	3.87 (2)	10.09 (2)
Campbell 9/91	<1.5	.	8.51	3.83	7.22	26.11
Above BS 5/94 thru 4/95	1.00	1.06 (3)	<0.40	7.94 (3)	16.21 (4)	37.9 (4)
Barton Springs 4/95 thru 7/95	<3.23	0.76 (3)	7.27	14.11 (4)	11.49 (4)	27.75 (4)
Barton Creek Mouth	3.87	.	4.08	4.50	18.51	38.23
Screening Levels						
TNRCC 85th %ile	6.600	1.140	19.000	18.000	40.000	83.000
TNRCC 50th %ile	3.500	0.350	9.640	7.340	10.600	40.200
TNRCC 15th %ile	1.600	0.100	4.000	2.210	3.200	18.000
ER-L	33.00	5.00	80.00	70.00	35.00	120.00
ER-M	85.00	9.00	145.00	390.00	110.00	270.00

The number in parentheses indicate the number of data points used to calculate the average value to the left.

Source: COA/DUD Database 1991-1995, TNRCC 1996, NOAA 1991

Figure 3.40

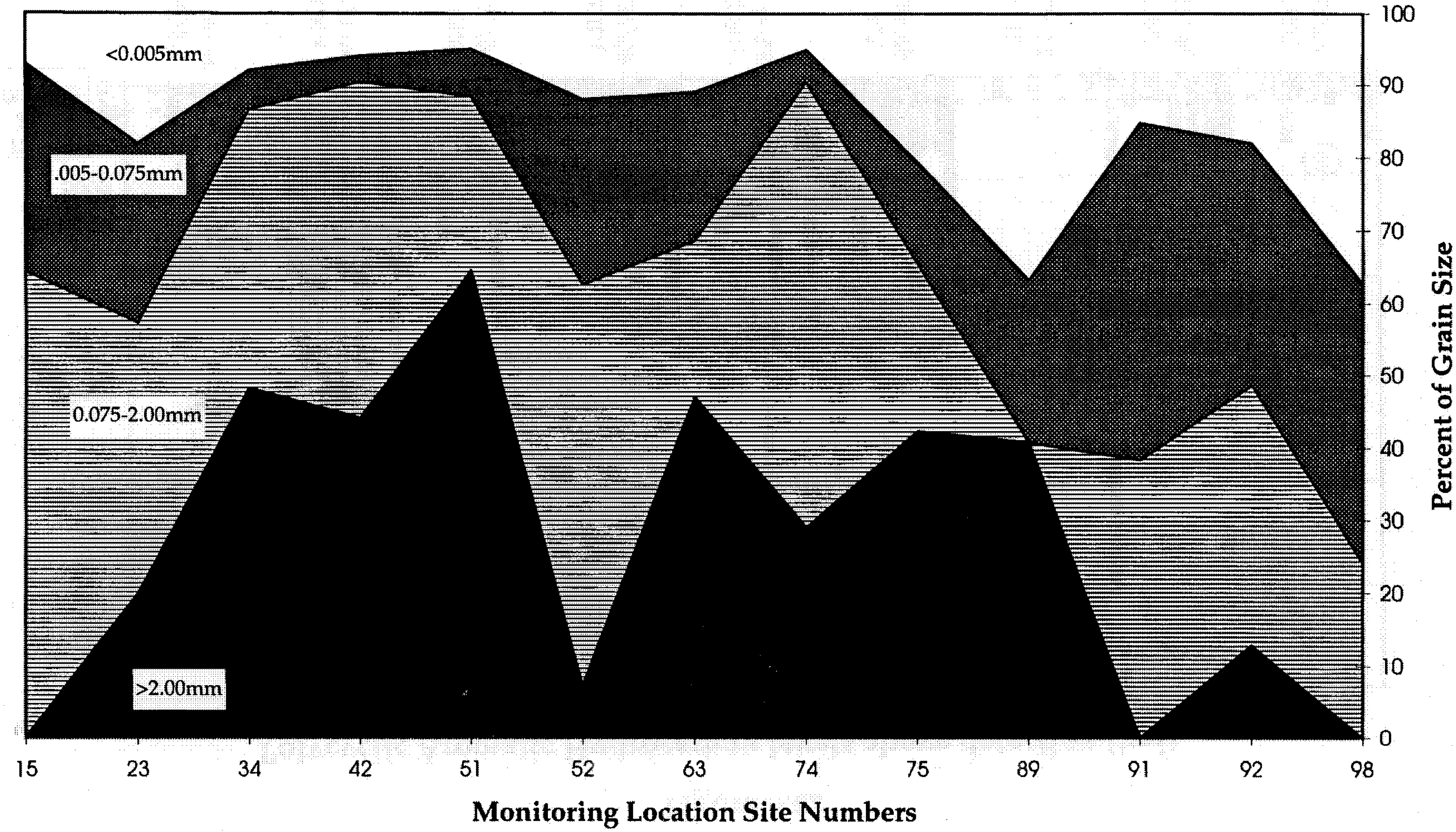
Barton Creek Sediment Metal Concentrations 1991-1995



Source: COA/DUD Database 1991-1995

Figure 3.41

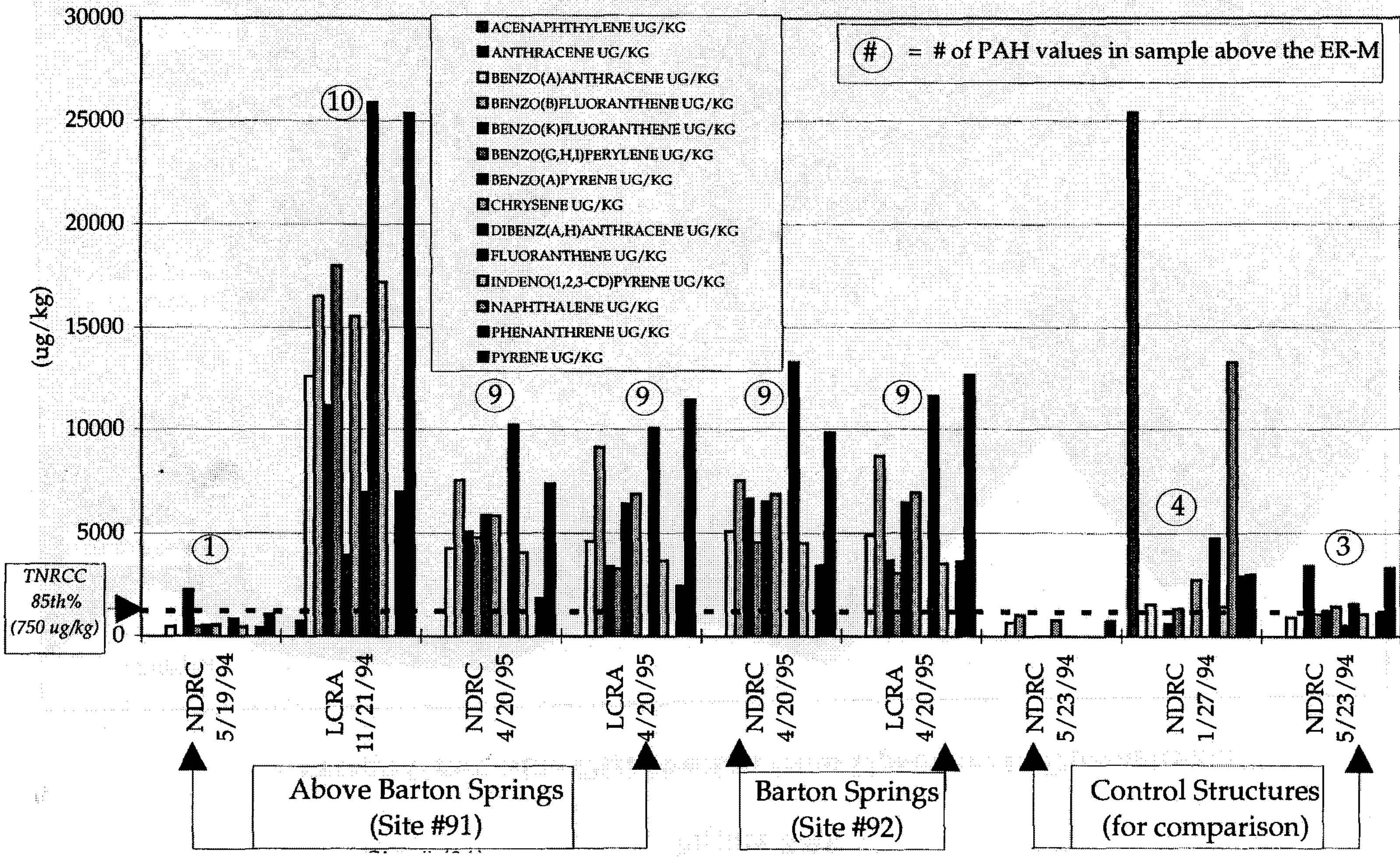
Average Grain Size Distribution from Upstream to Downstream



Source: COA/DUD Database 1991-1995

Figure 3.42

Polycyclic Aromatic Hydrocarbon levels above detection limit



Source: COA/DU Database, 1991-1995

Table 3.15 Pesticide Values From Above Barton Springs on November 21, 1994

Pesticide (ug/kg)	Detected Values (ug/kg)	TNRCC 85th percentile (ug/kg)
Aldrin	27.9	1.25
DDD	746.0	6.93
DDE	7.6	11.0
DDT	25.3	7.5
Delta-BHC	559.0	7.30
Endosulfan I	328.0	9.05
Endrin	530.0	2.45
Gamma-BHC	17.7	n/a
Heptachlor Epoxide	5.07	2.0
Heptachlor	232.0	1.0
Lindane	17.7	1.35

3.4.4 Discussion

The purpose of sediment sampling on Barton Creek has been to detect the presence of pollutants which might be below detection limits in water samples but due to their accumulation in sediments, may provide a more complete record of nonpoint source pollution. The data presented here provide an overview of the general status of the quality of sediments found in Barton Creek. Long term trend analysis in this data set demands very consistent frequency and methodology over a long period of time. Sediment sampling programs required by the Environmental Integrity Index to be used in the Drainage Utility masterplan will allow long term trend analysis at a later point in time. The sediment data gathered do allow for conclusions to be made about the presence and/or concentrations of many standard sediment quality constituents on Barton Creek.

Only three metal concentrations (two cadmium and one arsenic) exceeded the evaluation guidelines used in this report. All three exceeded the TNRCC 85th percentile, and one cadmium concentration exceeded the NOAA ER-M. Two of these higher concentrations were reported from one sample collected at site # 15 which is a rural, undeveloped site, where metal concentrations should be much lower than this anomalous value. All other variables from the metal data set were reported at low or non-detectable concentrations.

A comparison of lead, copper, and zinc concentrations show that although they vary from site to site, they increased from upstream to downstream (Figure 3.40). This may be the result of difference in grain size distribution between samples. Grain size distribution data indicated that higher concentrations of fine-grain material accumulated at the downstream sites (Figure 3.42). Normalization of the metals' data for grain-size indicated that a higher concentration of metals occurred at the site 51, which had low values but also a low fraction of fine grain sediments. These results may indicate that tributaries to Barton Creek were depositing sediments more concentrated in heavy metals than the background conditions were indicating. However, additional data would be required to confirm this conclusion.

At four dates, levels of PAH's at Barton Springs and the site immediately above the pool were above EPA biological effects levels (Figure 3.41). However, initial toxicity tests, using Microtox bioassays, did not verify this information. Benthic macroinvertebrate data from these sites indicated that they were scoring lower than upstream Barton Creek sites, but they scored equally or slightly better than downstream sites at other urban creeks. The high levels of PAHs at sites 91 and 92 do not appear to be dramatically impacting the benthic macroinvertebrate population, according to bioassessment surveys. Additionally, organochlorine pesticides were found above detection limits in one sample set at the Above Barton Springs site. The increase in concentrations in this area could be attributed to the accumulation of contaminated sediments at this most downstream site, from the discharge of Edwards Aquifer springs or storm runoff from nearby residential and commercial development. PAH and pesticide levels at sample sites on Barton Creek above the Barton Springs area showed no significant concentrations.

3.4.5 Conclusions and Recommendations

Interpreted against NOAA biological effects levels and TNRCC screening levers, concentrations of sediment constituents were not of concern, except for the area in and around Barton Springs. This area showed indications of pollutant loading due to its orientation at the downstream side of the watershed, its proximity to development and construction, and/or its hydrologic status as a recipient of Edwards Aquifer ground water from Barton Springs.

The sediment data collected on Barton Creek were difficult to evaluate because samples were collected during various studies, leading to a small number of samples per site and inconsistencies in sampling procedures. Any future monitoring or data analysis should have standard study design practices and the use of sediment traps, which allow for quantification of loading rates within each sediment grain size class. In addition, it is recommended that some screening level be used initially (immunoassays or indicator parameters), and that full suites of toxics be added when detected.

Two screening tools are recommended; site specific sediment quality criteria (SQC) for organics and SEM/AVS (simultaneously extracted metals/acid volatile solids) ratios for metals. These methods are the preferred indicators of contaminant bioavailability at the EPA and TNRCC and are based on the idea that the toxic effect of sediment to benthic organisms is determined by the extent to which a chemical is bound in sediments and not the total chemical concentration (TNRCC 305b. 1997).

Development of useful sediment quality criteria must take into account the biological response to sediment chemistry. Chemically based methods may be useful for setting global guidelines but should always be supplemented with biologically based local or regional criteria (R. Baudo. 1990). Site specific bioassay data, combined with SQC and SEM/AVS values is currently the recommended approach to evaluate the complex and important information stored in stream sediments.

4.0 BIOLOGICAL ASSESSMENTS

4.1 INTRODUCTION

The health of the Barton Creek ecology has always been a concern of City of Austin residents. This concern has resulted in several biological assessments undertaken by the Drainage Utility and predecessor departments in the last five years. This section summarizes a three year comprehensive study that examined biological tools for the assessment of nonpoint source pollution in the Barton Creek Watershed (COA, 1996a). In addition, assessments of Barton Springs and the Barton Springs salamander (*Eurycea sosorum*) are provided. The current status of salamander surface populations, along with vegetation and algae conditions in the pool are presented as ongoing studies. Additionally, a brief overview of Barton Springs ecology, flora, and fauna provides context for the Barton Springs data.

4.2 BIOASSESSMENT GRANT

The following is an overview of the comprehensive study by Environmental Resource Management (ERM) staff assessing biological monitoring tools in the Barton and Onion Creek watersheds. The full report is available at the ERM office and includes a detailed description of the study methods and technical analysis of all project data. The Bioassessment Project analyzed both Barton and Onion creeks, however, this review focuses on those findings that pertain to Barton Creek or give context to Barton Creek's biological status.

4.2.1 Introduction

During the past decade, the City of Austin (COA) has implemented a series of studies to document the relationship between increasing urbanization and the resulting impacts of nonpoint source pollution on the chemical water quality of streams within the City's jurisdiction. The pilot project *Bioassessment Strategies for Nonpoint Source Polluted Creeks* was designed to develop and evaluate biological monitoring techniques in Central Texas streams with varying levels of impairment due to nonpoint source pollution. During the past decade biomonitoring techniques for streams and rivers have received widespread acceptance from the US Environmental Protection Agency (USEPA) and state and local agencies responsible for the monitoring and assessment of water quality within their jurisdiction. This study provided a unique opportunity for the analysis of intermittent streams using biomonitoring techniques which were developed in areas dominated by perennial streams. The final report of the Bioassessment Grant was prepared in cooperation with the Lower Colorado River Authority (LCRA) under the authorization of the Texas Clean Rivers Act through a pilot project grant from the Texas Natural Resource Conservation Commission (TNRCC).

The major goals of the study were to investigate and document current levels of physical and biological impairment in two watersheds with varying degrees of land use development, to correlate various biological community conditions with physical and chemical indicators of nonpoint source pollution, and to develop effective long-term monitoring and assessment techniques for the Central Texas region.

4.2.2 Methodology

Project staff reviewed methodologies for the assessment of water quality, habitat, physical integrity, chlorophyll *a*, benthic macroinvertebrate communities, diatom communities, and quantitative measures of algae cover. When necessary, existing protocols developed by the TNRCC or EPA were modified based on data for the Central Texas Eco-region.

Following initial protocol development, project staff cataloged potential study sites by identifying all of the stream riffle areas within the study reaches of Barton and Onion creeks with appropriate habitat and substrate for benthic communities (Plate 5). After site selection, water quality, habitat, and biological data were collected at Barton and Onion Creek study sites on a quarterly basis. The intermittent nature of these Central Texas streams proved to be a major challenge, not only for data collection and analysis, but also for the identification of relationships between nonpoint source pollution and impairment to biological communities. This is especially evident during periods of moderate to extreme drought in Central Texas such as summer 1993 and the spring and summer 1996.

4.2.3 Analysis and Conclusions

ERM staff used a wide variety of analysis techniques to interpret the data obtained by this study. Univariate statistics describing the data sets were presented and evaluated for both watersheds. Land use at several watershed and subwatershed scales was analyzed in statistical comparisons to water quality and biological data. Site and creek comparisons were made using multiple regression combined with principal components analysis to explain variation in biological parameters using environmental variables. Multivariate statistics were also used to search for an optimal model of chemical water quality using benthic macroinvertebrates, diatoms, and field data. After examining the results from these analyses, the principal conclusions of the study can be summarized as follows:

Water Quality:

- The overall chemistry in the two study creeks was quite different. Several significant differences were found between the mean concentrations of water quality parameters on Barton Creek and Onion Creek. Total dissolved solids, total suspended solids, nitrate and nitrite-nitrogen, and total phosphorus were all significantly higher in Onion Creek than in Barton Creek. Flow rate and pH were significantly higher in Barton Creek than in Onion Creek.

- Consistent relationships were identified between land use and two important water chemistry parameters - total dissolved solids and nitrate+nitrite nitrogen. Nevertheless, the radical fluctuation in flow rates during this study emphasized temporal variation in water chemistry concentrations and minimized the influence of spatial, or land use differences between sites.

Both Barton and Onion creeks exhibited low levels of nutrients at upstream sites. The low nutrient levels resulted in limited productivity and relatively low levels of biological abundance and diversity at upstream sites. As the nutrient levels and flows increase at downstream sites, abundance and richness increase also. This condition of low abundance and diversity at upstream sites, observed by Ward and Stanford in their study of altitudinal zonation (Ward, J. V., 1983), is the opposite of the traditional model of ecological integrity, in which it is assumed that unimpacted biological communities exhibit higher levels of abundance and diversity than communities affected by natural and human-caused disturbances.

Chlorophyll *a*:

- The chlorophyll *a* means were different between the land use groups on Barton Creek. Sites with higher levels of residential housing and golf course land use in their immediate contributing watersheds had significantly higher chlorophyll *a* and pheophytin values than sites with lower levels of each of these land uses nearby. However, the relationship of chlorophyll *a* to baseflow water chemistry data were not significant, suggesting that the measure of algal biomass through chlorophyll *a* is a more sensitive indicator of nutrient enrichment from nonpoint source pollution than routine water quality sampling of baseflow.

Benthic Macroinvertebrates:

- Benthic macroinvertebrate species richness and percent dominance of the most dominant taxon, two bioassessment metrics recommended by the EPA, were not significantly correlated to any measured water quality parameters. Although the EPT index (Ephemeroptera/Plecoptera/Tricoptera index) was correlated to various measured chemical constituents, this metric was not consistent between creeks. Similar results were found with the Hilsenhoff Biotic Index (HBI) of pollution tolerance. The EPT/EPT+Chironomidae index, though strongly related to flow rate at the time of sampling, appeared to be the most closely related to water chemistry of all the metrics assessed.

- Development in Barton Creek is still in the early stages, with current impervious cover estimated at six percent in the study reach. Onion Creek, which is farther along in the development process, has impervious cover estimates of 10 percent in the study reach. The findings of this report suggest that the macroinvertebrate community is responding more dramatically to water quality variation in Onion than in Barton Creek. Creeks with higher mean levels of water column nutrients than Barton may have a more consistent response to chemistry by the macroinvertebrate community. In general, the macroinvertebrate data from the Bioassessment Grant indicate that current levels of biological impairment in Barton Creek are extremely low.

- Although most lotic biological communities are subject to temporal variation, it appears from project data that the stream macroinvertebrates had a particularly strong response to both season and flow, which overwhelmed all other documented variables.

Diatoms:

- Overall, the diatom community metrics were better than the benthic macroinvertebrate metrics at differentiating between variation in water chemistry and land use. Consistent site level variation was more common in Onion Creek than in Barton Creek, suggesting that there is a minimum level of chemical constituent concentrations beneath which these metrics cannot effectively differentiate.

- The relationship of the diatom community to nitrogen with respect to flow and season suggests that diatoms are more closely tied to the water chemistry at the time of sampling than are benthic macroinvertebrates.

- The largest variation in the diatom samples occurred between the communities on Onion Creek and the communities on Barton Creek. The next level of variation when both creeks were examined together was between sites within each creek. Both of these variables, creek and site, are spatial, suggesting that diatom community structure is strongly spatial. Strong and consistent spatial variation in a biological community is one characteristic of a good biotic indicator of environmental effects, such as land use.

- On both Barton and Onion creeks, diatom community changes were related distinctly to watershed changes due to levels of development as indicated by land use breakdown.

Temporal variation (season, flow):

- The intermittent nature of these streams makes it difficult to discern between impairments due to physical perturbations (e.g., significant changes in flow and temperature) and those resulting from human activity such as habitat alteration, or increasing impervious cover and development in the watershed.

- Extended periods of flow are required for mature biological communities to develop at the study sites. Study results indicated that during extended dry periods, biological communities are unable to survive and such communities are lost as indicators of cumulative effects. As surface flows return to the mainstem of the creeks, the substrate is slowly recolonized by periphyton and benthic macroinvertebrates.

- All relationships between biological communities and environmental parameters other than flow found in this study are conservative estimates because of the extreme flow variations during the project. Finding correlations in spite of the radically changing flow environment suggests that these relationships would have been stronger during more moderate flow years.

- For Barton Creek between Hwy 71 and Lost Creek Blvd., a comprehensive database describing benthic macroinvertebrates and diatom communities has been established as a result of this project. This information provides a baseline for comparison with biological conditions which may develop in the future.

4.2.4 Recommendations

The conclusions above suggest ways in which the utility of bioassessment methods could be improved in intermittent streams when nonpoint source pollution is the impact of interest. Project analysis and results have pointed to several additional study and development areas. These recommendations are summarized as follows:

- Biological sampling in the Austin area should continue, but should also take into account the sampling and community structure issues set forth in the Bioassessment study (COA-ERM/WRE 1996-01).

- Development of an ecological model that accurately depicts the water chemistry and aquatic community structure in the Central Texas ecoregion is recommended. An ecological model for Central Texas must account for the low nutrient levels upstream and increasing biological diversity and abundance downstream as nutrients and flow increase. By developing an accurate model of benthic community development and succession in these Central Texas streams, researchers will have the baseline information necessary to discern between impairments due to natural changes and those that result from human-caused activities.

- Biological monitoring on a regular basis is necessary to document the recolonization and development of the benthic biota. Long term monitoring over several cycles of dewatering is recommended to provide meaningful data despite flow changes.

- After looking at three scales of spatial analysis, it was determined that land use on a watershed scale had the strongest relationship to water quality using multivariate statistical methods of data condensation including principal components analysis. Mitigation of human-caused influences on water chemistry requires the adoption of a whole watershed management approach.

- To retain the natural biological integrity of local creeks, flow regimes must retain their natural cycles. Radical human-caused changes in the flow regimes of urban watersheds will alter resident biological community structures. It is recommended that City policymakers determine how best to regulate developed and, perhaps more importantly, developing watersheds to minimize changes in flow patterns.

4.2.5 Additional Uses of Bioassessment Data

One of the advantages of having the well developed biological data base from the bioassessment grant is its use as an assessment tool for the Drainage Utility Masterplan.

One of these tools is the Environmental Integrity Index (EII). During three consecutive years (1994, 1995, 1996), ERM staff conducted multi-faceted environmental surveys of selected urban and non-urban watersheds in Austin, including Barton Creek. Multiple sites in each watershed were sampled across a range of environmental quality indicators:

- Aquatic Life - Benthic macroinvertebrates, diatoms and habitat quality
- Water Quality - A suite of physical and chemical indicators
- Sediment Quality - A chemical evaluation of deposited sediments
- Contact and Non-contact Recreation - Evaluations of the recreational value of Austin streams
- Physical Integrity and Stream Stability - Assessing channel erosion and bank vegetation

Data from the last three years were indexed and evaluated in a comprehensive report which will be available at the ERM office beginning in the summer of 1997. Barton Creek was used as a reference because of its high scores among the subset of Austin watersheds evaluated in the Drainage Utility Masterplan. The data and experience that resulted from the bioassessment grant funded project were also invaluable in the formulation and development of the EII.

4.3 BARTON SPRINGS SALAMANDER MONITORING

4.3.1 Introduction

On February 17th, 1994, the U.S. Fish and Wildlife Service (USFWS) proposed adding the Barton Springs salamander (*Eurycea sosorum*) to the list of endangered and threatened wildlife which receive federal protection under the Endangered Species Act. Named after the "Save Our Springs" (SOS) citizen clean water referendum and described as a new species of *Eurycea* by Drs. Chippendale, Price and Hillis in *Herpetologica* (June, 1993), this salamander species, whose only known habitat is in the springs in Zilker Park, has been very prominent in environmental and political issues in Austin for the last five years. This species was listed as a federally protected endangered species on April 30, 1997, by the

USFWS. In the listing of the salamander, included as Appendix I, the USFWS stated that "the primary threats to the Barton Springs salamander are degradation of the quality and quantity of water that feeds Barton Springs due to urban expansion over the Barton Springs watershed" (Fed. Reg., 1997). In response to the federal listing, the City of Austin will apply for a 10 (a) permit for the continued operation of Barton and adjacent springs, participate in the USFWS Salamander Recovery Team, and review the efficacy of current City and State watershed ordinances with respect to protection and long-term viability of the species.

In April 1994, the Austin City Council unanimously passed a resolution supporting the USFWS in their proposed listing of the Barton Springs salamander as an endangered species. In July of 1993, City of Austin, ERM staff biologists developed a cost effective method to routinely monitor salamander, plant and invertebrate populations in Barton, Eliza and Old Mill Springs. Monthly monitoring of the ecology and biota of the springs provides vital information documenting the variability in population distributions and ranges. Additional goals of the monthly surveys are to provide a long-term tracking method to monitor effectiveness of habitat restoration efforts and non-toxic maintenance procedures.

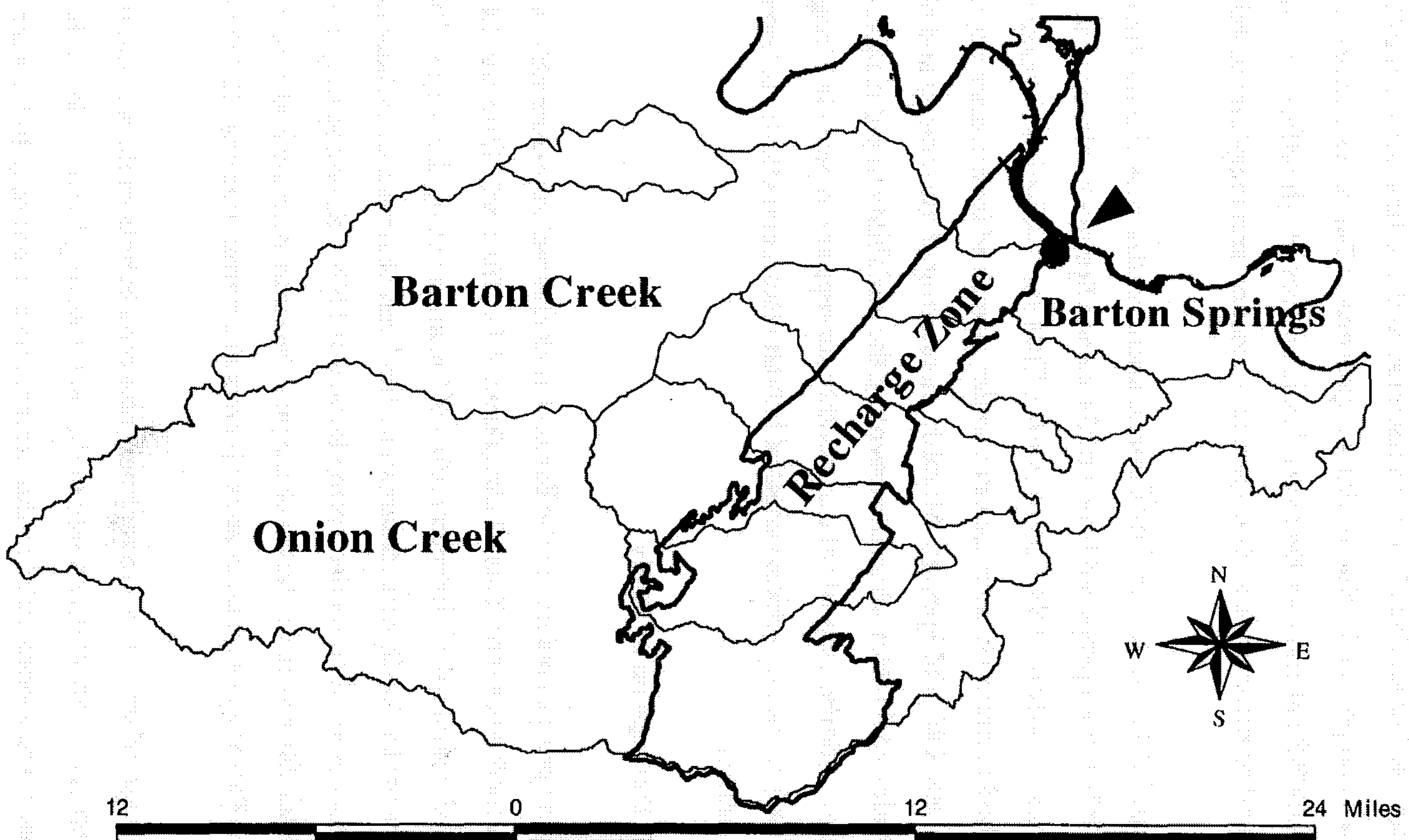
4.3.2 Description of Study

Barton Springs Pool lies in the Barton Creek channel approximately one kilometer upstream of its confluence with Town Lake (Figure 4.1). The pool, Eliza and Old Mill springs are all located within a 0.5 kilometer radius of the main spring discharge. These three locations are where the Barton Springs Salamander has been observed and where monitoring has been focused. A smaller, related spring known as Upper Barton Springs near the Barton Creek channel 100 meters upstream of the pool, has only recently had a documented observation of the Barton Springs salamander (Personal communications - D. Johns, 1997).

Although salamanders are routinely observed in both of the secondary springs, most City of Austin efforts are concentrated in the center, spring-head section of Barton Springs pool. Six transects were established in this center section, extending to the edges of the salamander habitat (Figure 4.2). Surveys are scheduled once each month and following natural and unnatural disturbances (storms, spills, large cleaning events, etc.).

Figure 4.1

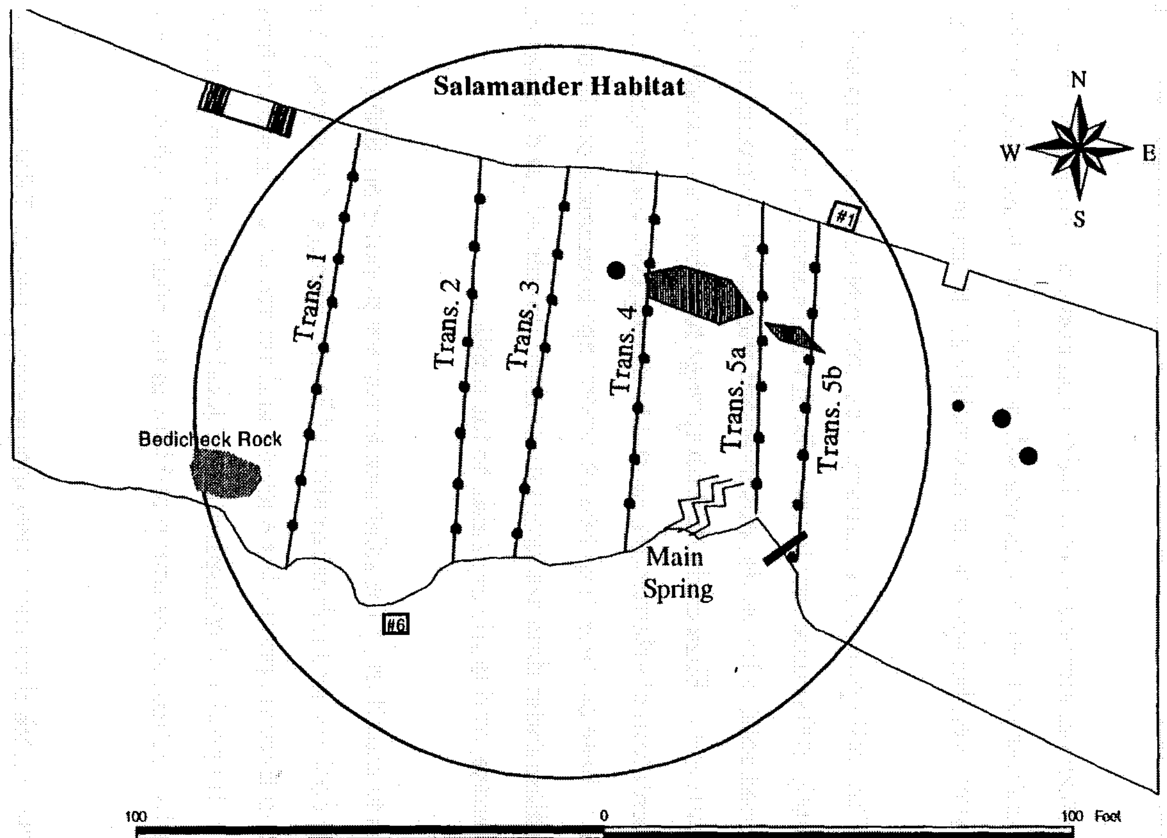
Barton Springs Location and Contributing Watersheds



Source: COA/DU GIS database

Figure 4.2

Salamander Survey Area and Transects



Source: COA/DU GIS database

One observer, using SCUBA, traverses each transect, stopping every ten feet and searching carefully inside of a one square meter area, documenting pertinent biota and substrate. For each of these one square meter transect sites the following data are gathered:

Station	Substrate	Depth	Biota
10', 20', 30', etc...	Bedrock, Cobble, (2-4cm diam)	3', 15', etc...	1 Sal (J, A), Crawfish, Amphipod, Darter, etc...

The other observer surveys known habitat sections, or "hot spots" near major and minor springs and fissures these additional salamander counts are added to the closest transect site. Each staff member spends approximately 2.5 hours to survey all transects.

Eliza and Old Mill springs are contained by concrete or stone walls and are each approximately 300 square feet in area. Both were surveyed quarterly by two staff members, who tabulated total salamander observations and noted environmental conditions. Recently, surveys at Eliza and Old Mill springs have been increased to monthly following the documentation of salamander mortality during pool lowerings under low flow conditions. These surveys take two observers approximately one hour at each site. All available salamander data are carefully verified, tabulated , and stored in the Drainage Utility database, and made available to the public.

In addition to monitoring the salamander surface population, ERM staff are involved with the general ecology and habitat quality of Barton Springs. On a yearly basis, the vascular vegetation in Barton Springs is reviewed and expanded by dissemination of existing stands of plants in the pool and transplanting of local populations from Barton Creek and Town Lake. The three most successful plant taxa in the pool are *Sagittaria, Potamogeton,* and *Ludwigia.*

In conjunction with the salamander monitoring program, ERM staff have been closely involved with Parks and Recreation Department (PARD) staff to assist with the development and implementation of effective, non-toxic maintenance procedures. Sedimentation, slipperiness due to algae growth, and algae blooms have all been maintenance issues since monitoring of the salamander began four years ago. Staff members have initiated studies to research and develop maintenance practices that benefit the salamander, the Citizens of Austin, and the pool staff (COA, 1996b).

4.3.3 Results

Salamander surveys:

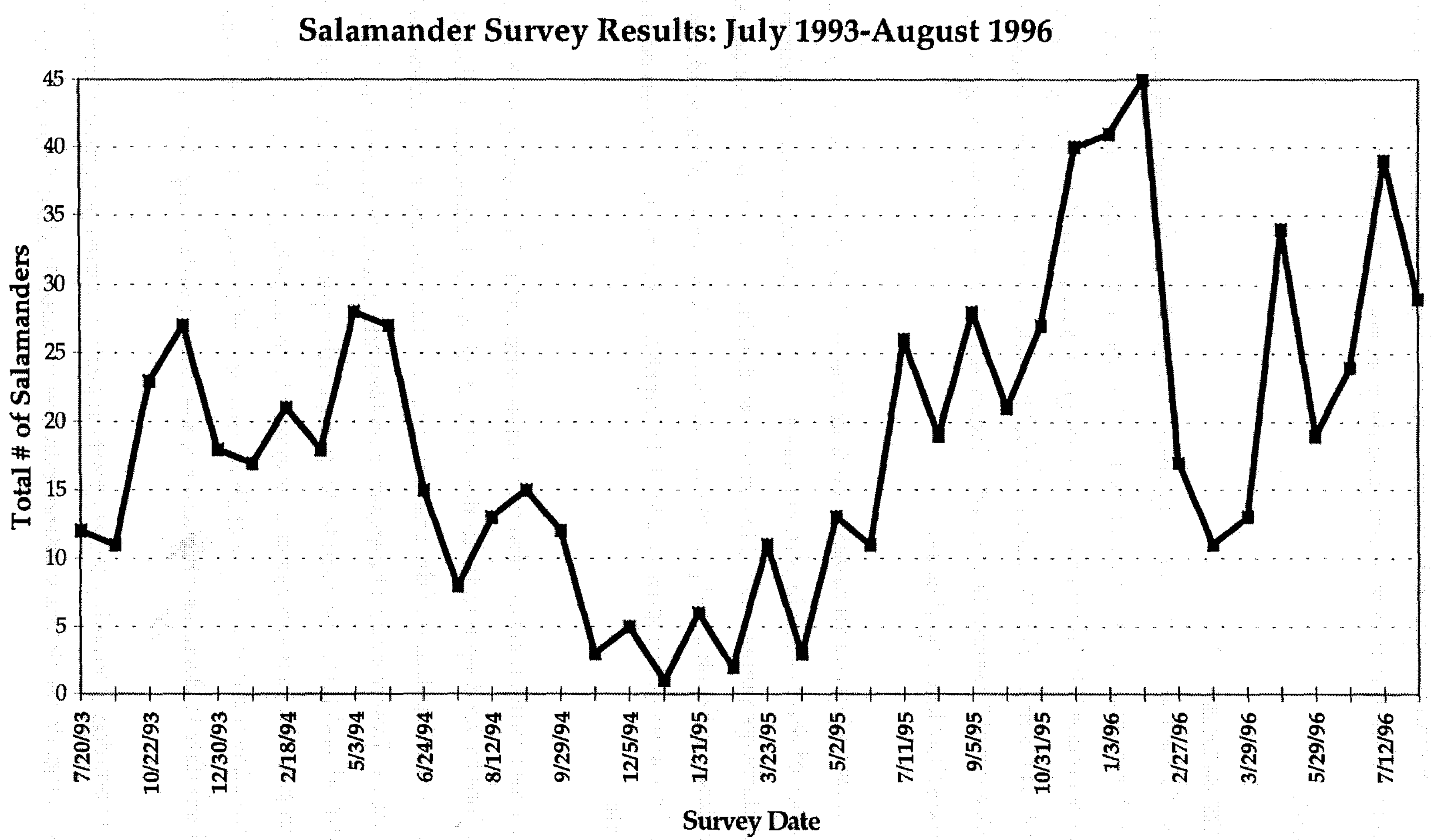
From June 1993 to the present, monthly surveys of the Barton Springs pool salamander population have been conducted according to the above methods. The total number of salamanders counted during these surveys ranged from one to 45 in the main springs, with the highest counts in the Fall/Winter of 1995/1996 (October to February) and the lowest between October of 1994 and June of 1995 (Figure 4.3). Current methodologies are unable to estimate the subsurface populations.

Although the monthly counts have varied from one to 45 during this study, the distribution and frequency of observation in certain areas are more predictable. Barton Springs pool has numerous discharge points around the central section but only five or six that are notable for higher flows and cobble and gravel substrate with a low degree of embeddness. Figure 4.4 shows the transects, hot spots and the total number of salamanders observed at each point to date.

The depth most salamanders are observed varies from one to five meters, with the majority of observations in the deep middle section of the pool, where the springs discharge. There is no viable habitat upstream of the first transect, only flat bedrock and concrete surface with no fissures. Downstream of transect 5b, cobble and gravel become embedded or covered with silt and there are no notable spring discharges. Transect 6, downstream (not shown), was part of initial surveys and continues to be spot-checked. No salamanders have been observed downstream of transect 5b or upstream of Transect 1, but routine checks are performed monthly to document the range of the current surface population.

Some of the variation in monthly survey totals appears to correlate to natural disturbances in the pool. Large or particularly intense rain events cause flooding from Barton Creek to

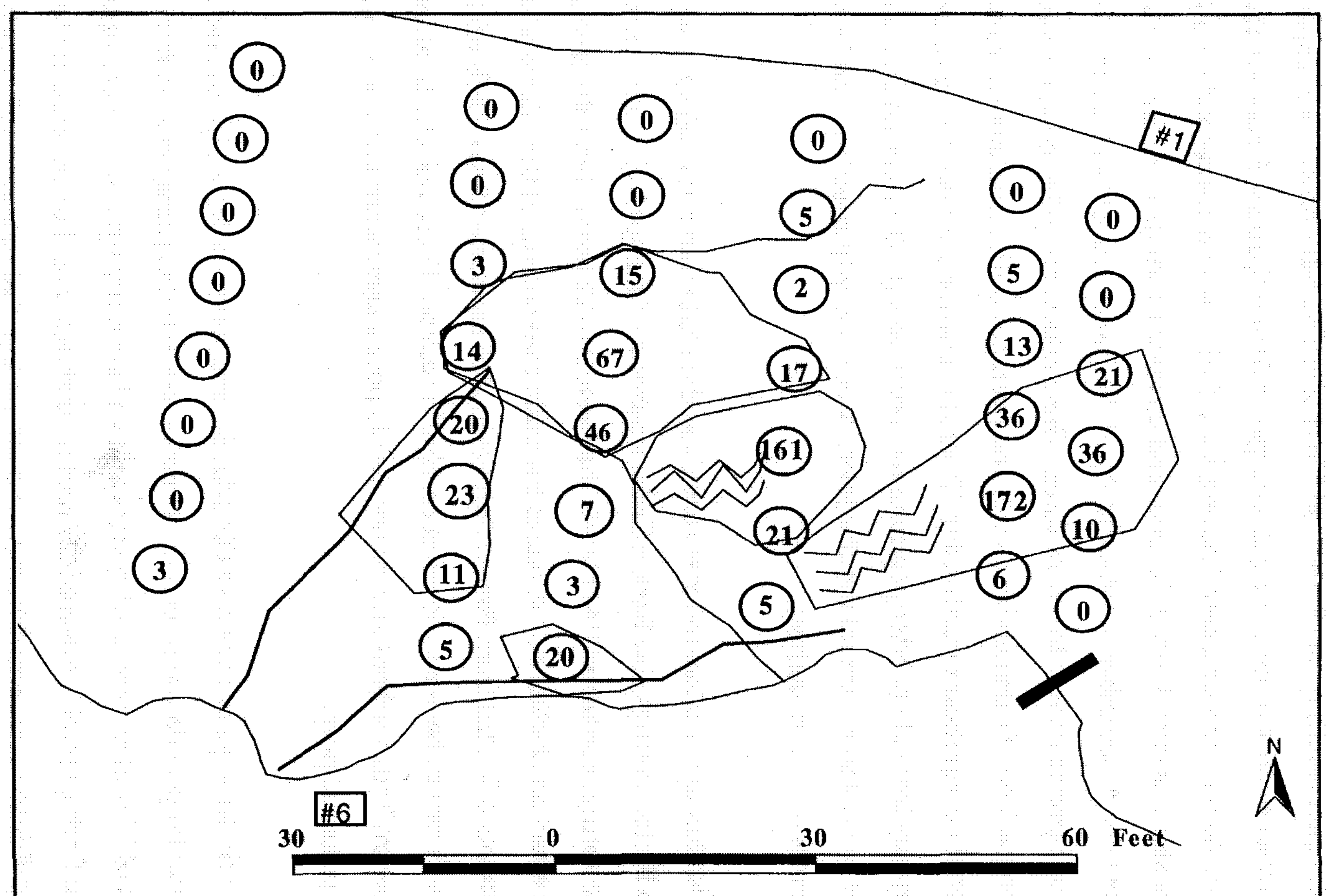
Figure 4.3



Source: COA/DU database 1993-1996

Figure 4.4

Salamander Distribution and Frequency of Observation
(Numbers indicate total salamanders counted to date at that location)



Source: COA/DU GIS database

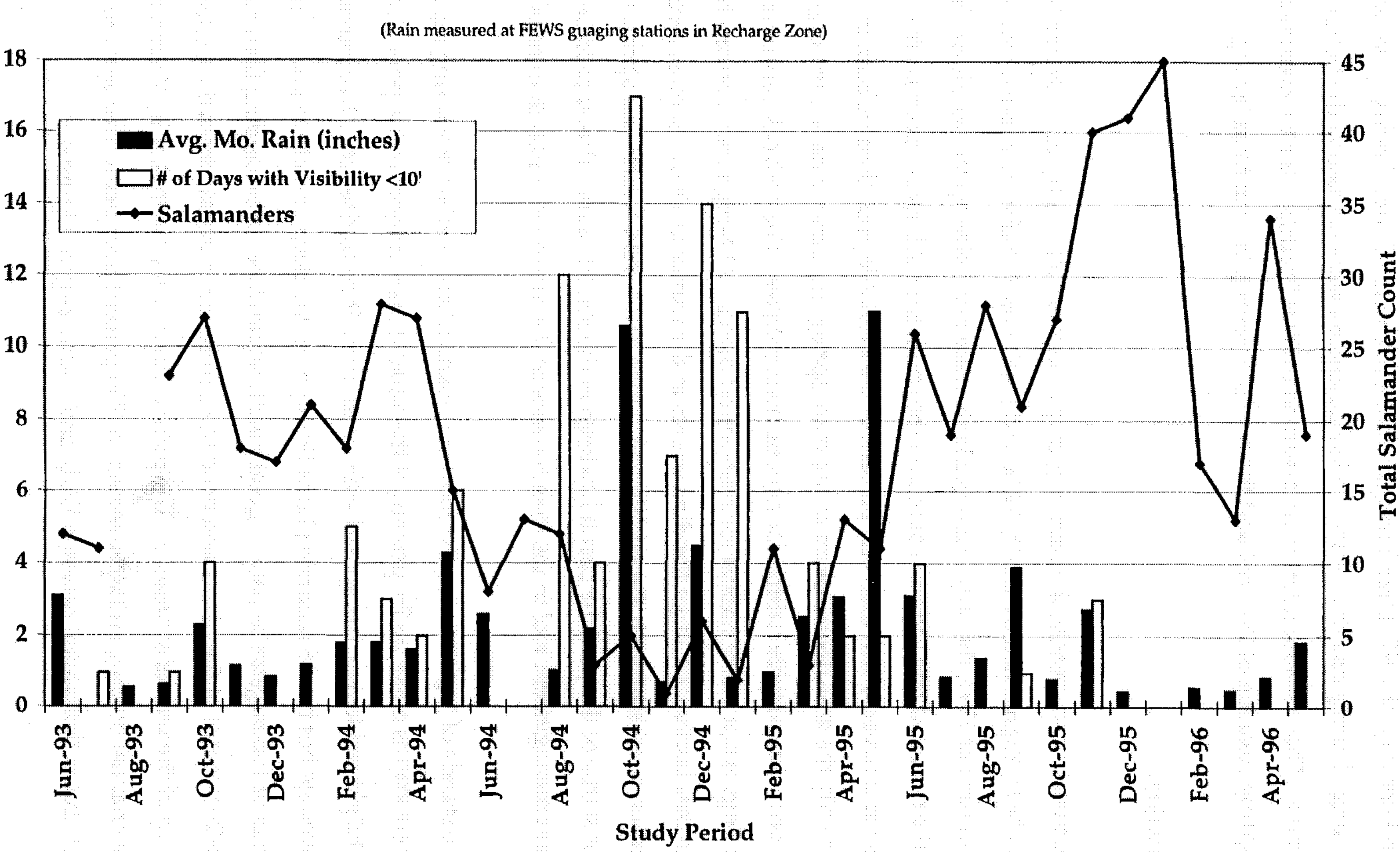
top the dam and dump large quantities of sediment and debris in the deep section of Barton Springs pool. The silt and debris cover salamander surface habitat, thus restricting the area of the pool that can support salamander surface populations. Rain events that do not flood the pool can cause the aquifer to discharge silt and sediment into Barton Springs pool, again resulting in siltation and loss of salamander habitat, accompanied by changes in the water quality of the spring discharges at Barton Springs. Figure 4.5 illustrates how salamander counts decreased during the fall of 1994 and winter and spring of 1995 after large storm events flooded the pool and increased turbidity. In the months of September, October and December of 1994 and April, May and June of 1995, Barton Creek flooded Barton Springs pool with stormwater. These effects are reflected in the salamander counts. A comparison of salamander counts and average aquifer discharge in Barton Springs showed no significant relationship (R^2=0.06); however, a positive lag correlation is possible. It appears that salamander populations may have a positive correlation to higher aquifer flows but not until several months later. More data will need to be collected for further temporal variation analysis.

In addition to the salamander survey data, the DUD staff have collected sediment samples from Barton Springs and Barton Creek upstream of the springs. Sediments from upstream of the springs contained PAH levels that were 2 to 22 times above the levels shown to have a toxic effect on *Hyallela azteca*, one of the main constituents of the salamander prey base. Sediments collected from Barton Springs in 1995 contained PAH levels 6.5 times above levels shown to have a toxic effect on *Hyallela azteca*. These pollutants, along with petroleum hydrocarbons and heavy metals pose a significant threat to salamanders and their potential prey.

Quarterly surveys in Eliza and Old Mill Springs have shown a high degree of variability in salamander population numbers. Water levels in both springs tend to fluctuate from a depth of 10 centimeters to 2.5 meters and will even dry up under lower aquifer flows when Barton Springs pool is lowered for routine maintenance. Public access makes them more susceptible to vandalism, littering, and tampering. Salamander surface populations have been found intermittently at both of these spring locations since surveys were initiated in 1993. Survey results have shown an increasing number of salamanders at Eliza Springs,

Figure 4.5

Salamander Counts vs. Monthly Rainfall and Turbidity Events



Source: COA/DU database 1993-1996

with a regular survey high count of 72 salamanders on March 27, 1997. During low aquifer flows in February of 1997, Eliza Springs became dry when Barton Springs pool was lowered for cleaning. During one dry period, 188 salamanders were rescued at the bottom of the empty pool. These salamanders were returned to Eliza Springs after the completion of the major spring cleaning of the pool and the return of spring flow to Eliza Springs.

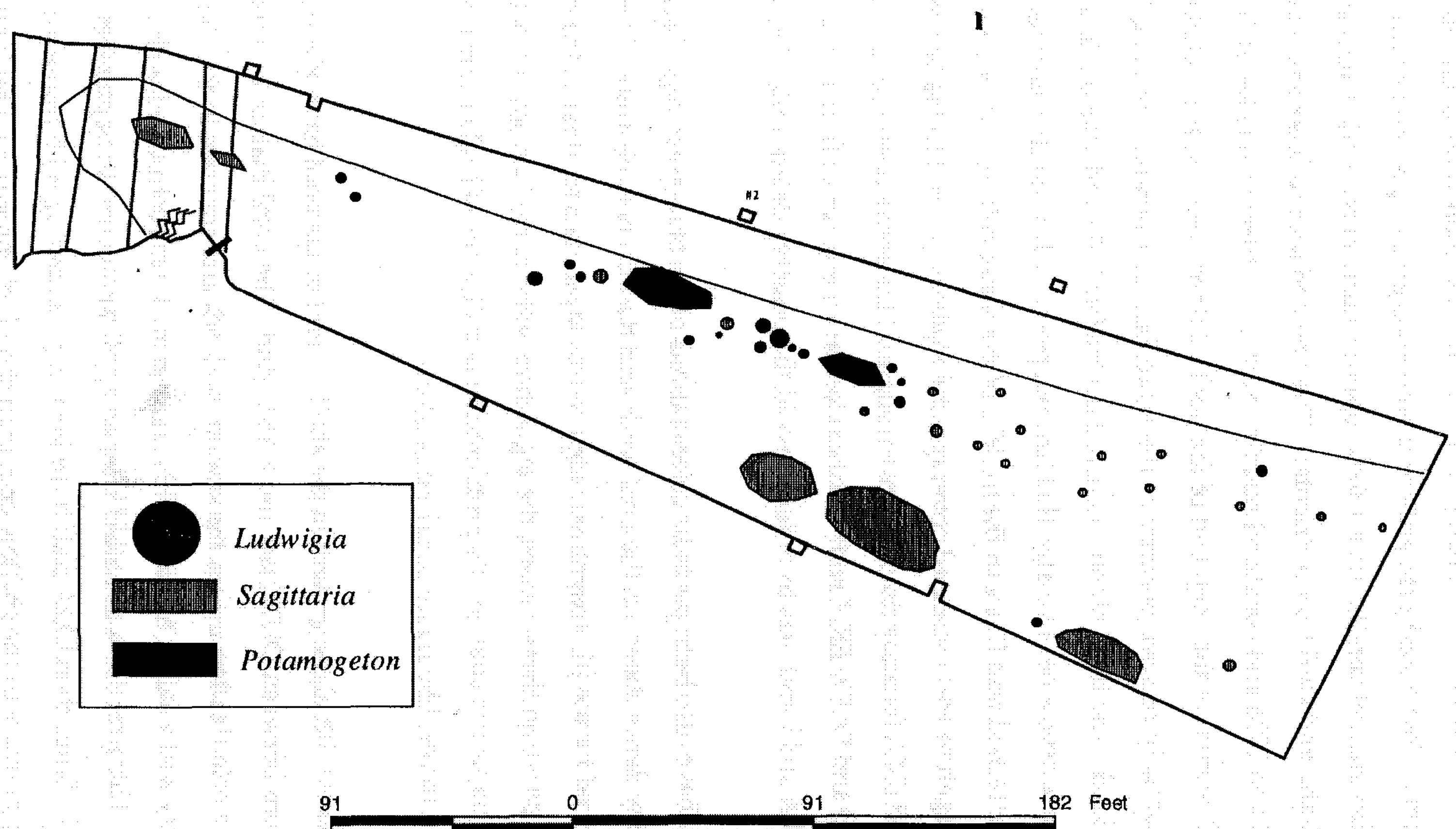
Revegetation:

Approximately once yearly, the standing crop of aquatic macrophytes in Barton Springs Pool has been augmented by DUD/ERM and PARD staff. Before the initial revegetation project in June of 1993, the only existing plants were two *Potamogeton* stands on the north side of the pool and one *Sagittaria* stand on the south side. All were about six feet in diameter and covered less than one percent of the available pool channel bottom. This includes only the area downstream of the main spring discharge where there is gravel and silt that provides suitable habitat for aquatic macrophytes. The bedrock substrate above the main springs is not viable habitat for root-bound plants. Although initial efforts had only small success because of large flooding events in the winter of 1994, the most recent revegetation combined with the established stands and a mild winter and spring have left the plant status of the pool the best it has been in the last 10 years. This should be a significant management tool in the maintenance of the salamander populations of the pool.

The large stands of *Sagittaria* are the most successful plants and are spreading rapidly. The 22 separate stands make up 75 percent of the aquatic macrophytes in the pool. *Ludwigia,* with its bright red leaves, has spread well on its own. It comprises only five percent of the plant coverage but has 16 separate plants throughout the deep end of the pool. The original two stands of *Potamogeton* remain in good health while slowing expanding their range. They make up 20 percent of the plants and need to be trimmed routinely from the surface to remain out of the way of swimmers. The plant community now makes up 7 percent of the available channel bottom, an improvement of 700 percent over plant coverage four years ago when this collaboration between DUD and PARD began (Figure 4.6).

Figure 4.6

Vegetation Status of Barton Springs Pool - August, 1996



Source: COA/DU GIS database

Algae:

In four years of Barton Springs Pool monitoring, there have been three significant algae blooms. Comprised primarily of filamentous green algae, all occurred during optimal environmental conditions for these opportunistic organisms (warm surface water, adequate sunlight, and sufficient nutrients). The first and second blooms occurred in the spring of 1995 and 1996 and consisted mainly of attached filamentous *Rhizoclonium* which covered up to 70 percent of the deep end of the pool. Efforts were made by DUD/ERM and PARD staff to manually remove portions of the algae, but after several weeks the bloom naturally subsided. The third bloom occurred in October 1995 and was made up mainly of *Hydrodictyon*, a net-like alga that had not previously been documented in the pool. This alga is unattached and floats in the middle of the water column. After several weeks of propagation and increased coverage, the *Hydrodictyon* fell to the bottom when the weather turned cold, forming thick layers throughout the entire deep section of Barton Springs. PARD and DUD/ERM staff collaborated on an intensive effort to remove it manually using SCUBA and hand nets in order to avoid the possibly deleterious effects of decomposition.

There have also been periodic colonizations of the blue-green alga Oscillatoria, which grows in shiny dense sheets on the pool walls and the channel substrate. During the day, oxygen produced by the photosynthetic alga causes algal mats to float to the surface. At night, when photosynthesis ceases, the algal mats settle to the bottom and this cycle is repeated until conditions change. Its proliferation is indicative of higher nutrients, and warm temperatures, like many of the other algae.

Problems with algae growth in the shallow end of the pool have given rise to collaborative solutions between DUD staff and PARD staff. The combination of blue-green algae and diatom colonization makes the smooth bedrock and concrete in the shallow end extremely slippery and a safety hazard. This algae growth was controlled with chlorine for many years. This practice was halted after an application error in September 1992 caused a large fish kill. Since then COA staff have been experimenting with non-toxic methods to control the slipperiness in the shallow end, including high-pressure water blasters, heat, long term exposure to sunlight, and large abrasive rotary brushes. Mounted on the front of a small tractor, this five-foot wide nylon brush rotates and scours the bedrock in the shallow end, retarding the growth of the benthic algae that causes the slipperiness. This has been the most successful method so far, but still requires heavy equipment, 14 man-hours per week and periodic intensive drying since the brush does not completely halt the algae growth process. It is a temporary solution to a natural environmental occurrence. The shallow water, smooth bedrock and concrete, and warm conditions provide a perfect medium for algal colonization. Attempting to control the algae growth for the safety of Barton Springs patrons, while still protecting the ecological integrity and viability of the biological resources in the pool, provides an on-going challenge for DUD and PARD staff and management.

4.3.4 Conclusions

Surface populations of the Barton Springs salamander in Barton Springs pool have been monitored monthly for 38 months. Total monthly counts, although variable, have not increased above 45 individuals in the main springs. Considering the size and physical limitation of this unique habitat, and the nature of salamander populations in general, this population of Barton Springs salamanders is particularly subject to extinction in the event of any extreme disturbance, be it natural or anthropogenic (Bowles, 1995).

It is extremely important to continue to monitor any and all ecological fluctuations that may affect this species and its environment. Study data indicate that surface populations can be reduced drastically due to natural trauma (storm events) and the recolonization process may take as long as six to eight months. We have also documented the variability in the number of salamanders in the secondary springs. The Barton Springs salamander is responding to obvious environmental changes, but the more subtle chemical and physical changes that affect this organism have yet to be determined. In conjunction with monitoring, more work needs to be done on the salamander life history to determine how it is interacting with its environment. During COA involvement in studies of the Barton Springs salamander, specimens have been removed from Barton Springs and Old Mill Springs and placed in refugia, one at the Dallas Aquarium, in Dallas, TX and the other at the Midwest Science Center in Columbia, Missouri. Both have had some success with captive breeding but they are still in the initial stages of developing stable populations. The MSC population has recently been moved to a new facility at the San Antonio Zoo. These populations may provide a gene pool for eventual reintroduction should the wild population be extirpated. Through more scientific study of the salamander, we will be able to better understand the biotic and abiotic factors that determine the reproductive biology and long-term viability of the species.

Barton Springs has seen different management and citizen interests since its first dam was constructed, with some interests viewing it as a swimming pool that should be maintained as such, others as a unique aquatic ecosystem that should be preserved for its biological integrity. DUD and PARD staff have tried to find the common ground between these two positions. The success of the plant communities in the pool is an example of this collaboration. While the stands of *Potamogeton*, *Sagittaria* and *Ludwigia* provide excellent aquatic habitat for life in the pool and represent conditions above and below Barton Springs, they also anchor sediment and gravel, which reduces turbidity and stabilizes the beaches. The end result is a more efficient, healthier system that can satisfy the needs of the citizen/users and natural biota.

4.4 BARTON SPRINGS ECOLOGY

4.4.1 Introduction

At the eastern tip of the Barton Creek Watershed, the Barton Springs segment of the Edwards Aquifer discharges into Barton Creek one kilometer before it enters Town Lake. The large concrete pool constructed around the multiple spring head system in 1922 created a unique mix of natural and controlled dynamics. While an average of 32 million gallons of spring water flow into the pool every day from the aquifer, supporting a diverse population of flora and fauna that is unique to this system, the environment known as Barton Springs can be impacted by natural storm events and routine pool maintenance practices (e.g., the 1992 fish kill due to chlorine application). Regular maintenance now includes: water blasting, rotary brushing, firehosing, gravel dragging, and lowering and raising the water surface by 1.5 meters.

The main spring discharge points are in the central, deepest section of Barton Springs pool, where the limestone ledges drop down to a depth of 5 meters, and the long fissures and crevices direct spring flows out to the middle of the diving area. High velocity discharges around the spring heads keep the bottom relatively free of debris and sediment when aquifer levels are at or above normal, providing an abundance of large cobble, gravel and suitable habitat for the organisms that thrive here. Long-term isolation, constant water supply and temperature and nutrient rich waters create an environment that encourages development of diverse and unique populations.

The following list includes only those taxa that are common in Barton Springs, and those that are of special interest.

Plants: (Vascular Macrophytes)

1) Pond Weed - (*Potamogeton*)
2) Water Primrose - (*Ludwigia*)
4) Arrowhead - (*Sagittaria*)
5) Spikerush - (*Eleocharis*)

Algae:

A. Floating/Unattached:

1) *Hydrodictyon*
2) *Spirogyra*
3) *Mougeotia*

B. Benthic/Attached:

1) *Vaucheria*
2) *Rhizoclonium*
3) *Chaetophora*
4) *Batrachospermum*

5) *Oscillatoria*

6) Bacillariophyceae - Diatoms

Moss:

1) *Amblystegium riparium*

Animals:

A. Invertebrates -

1) Amphipods - *Hyallela azteca*

2) Crawfish - *Procamberis clarki*

3) Mayflies (Ephemeroptera) - *Stenonema* sp.
Baetis sp.
Hexagenia sp.

4) Caddisflies (Trichoptera) - *Helicopsyche* sp.

5) Damselflies (Odonata) - *Argia* sp.
Hetaerina sp.

6) True Bugs (Hemiptera) - *Cryphocricus* sp.

7) Snails - Physidae, Planorbidae

8) Planaria - *Dugesia*

9) Leeches - Hirudinea

B. Salamanders

1) Barton Springs Salamander - *Eurycea sosorum*

C. Turtles:

1. Red Ear Slider - *Trachemys scripta*
2. Snapper - *Chelydera serpentina*
3. Texas Cooter - *Pseudemys texana*

D. Fresh Water Eel(s) - *Anguilla rostrata* (Observed from 10/95 to present)

E. Fish:

1) Mexican Tetra - *Astyanax mexicanus*
2) Central Stoneroller - *Campostoma anomalum*
3) Red Shiner - *Cyprinella lutrensis*
4) Gray Redhorse (sucker) - *Moxostoma congestum*
5) Channel Catfish - *Ictalurus punctatus*
6) Flathead Catfish - *Pylodictus olivaris*
7) Blackstripe Topminnow - *Fundulus notatus*
8) Mosquito Fish - *Gambusia affinis*
9) Texas Log Perch - *Percina carbonaria*
10) Redbreast Sunfish - *Lepomis auritus*
11) Green Sunfish - *Lepomis cyanellus*
12) Bluegill Sunfish - *Lepomis macrochirus*
13) Longear Sunfish - *Lepomis megalotis*
14) Spotted Sunfish - *Lepomis punctulatus*
15) Spotted Bass - *Micropterus punctulatus*
16) Largemouth Bass - *Micropterus salmoides*
17) Guadalupe Bass - *Micropterus treculi*
18) Green Throat Darter - *Etheostoma lepidum*

4.4.2 Discussion

Although these springs discharge what appears to be an endless supply of fresh clean water, the reality of water issues in Central Texas indicate the potential for degradation due to increased demand and development of the contributing watersheds. The quantity and quality of the water of Barton Springs is directly dependent on the health of streams that feed the Edwards Aquifer. Increased runoff from urbanized areas, along with agricultural and human use via well withdrawal, toxic spills, and the cumulative effects of urbanization all can have potentially devastating effects on the health of the Springs.

When heavy rains fall in the watersheds west of Austin they wash whatever happens to be on the ground into the creeks that eventually flow into the Recharge Zone of Barton Springs. This runoff can transport into the aquifer everything from agricultural pesticides, lawn fertilizers, and bacteria to raw soil that has been exposed at construction sites. In addition, as development increases so does the amount of impervious cover (concrete, roofs, asphalt, etc.). More impervious cover causes water to run off faster and in greater quantities, since the water has no opportunity to filter into the ground and has no natural vegetation or obstacles in its path. Intense runoff or recharge events (storms) carry large quantities of storm water into the aquifer, and this runoff can rapidly move through the aquifer to the main discharge point at Barton Springs.

Sediment is also an important environmental factor in the pool. Some particulate matter (from either mineral or plant/animal sources) enters the pool from the aquifer through the springs; other sediment is washed over the dam during floods; and some detritus or particulate matter is generated during the routine cleaning process in the shallow end of the pool. All this fine matter tends to collect in areas of the pool where flow is slow or obstructions cause an eddy or a backwater. Buildup of fine sediments can cause problems with oxygen transport when the embeddedness of the substrate is so dense that the sediment layers are essentially impermeable to oxygen. The embeddedness causes black anoxic layers to form below the surface sediments. The lack of oxygen effectively kills most biology (with the exception of chemotrophs and lithotrophs) in or below these layers. Loss of protective habitat can also result from sediment buildup. The biota of the springs that inhabit the interstitial spaces between the cobble and gravel substrates are excluded from areas that are filled in by fine particulate matter. The loss of appropriate habitat makes these species unnaturally vulnerable to predators and alters the ecological balance of the pool.

During the past two decades, daily observers of Barton Springs have witnessed the decline and loss of aquatic macrophytes in the deep end of the pool, pool closings due to high levels of bacteria, algae blooms, and periods of poor visibility due to high levels of suspended solids discharging from the aquifer. Most recently, Barton Creek has been designated as non-supportive for the designated use of contact recreation due to high levels of fecal coliform bacteria concentrations over its entire length (TNRCC 305b Report, 1996) by the Texas Natural Resource Conservation Commission and the Barton Springs salamander has been listed as a federally protected endangered species by the US Department of the Interior (Fed. Reg. Vol. 62, No. 83, PP. 23377-23392). All of these events are indicative of the degradation of the ecological integrity and water quality in the contributing and Recharge Zones for the Barton Springs segment of the Edwards Aquifer.

In response to documented and anticipated changes to the integrity of the Barton Springs segment of the Edwards Aquifer, the City of Austin has actively pursued biological monitoring projects that provide valuable baseline data and long-term, cost-effective assessment tools. The grant funded Bioassessment Pilot Project (1993-1996) for Barton and Onion creeks provides detailed information concerning the fauna, habitat, and physical integrity of the two streams that contribute up to 75% of the recharge to Barton Springs. In addition, the Pilot Project evaluated the effectiveness of nationally accepted methods of biological monitoring and recommended protocols and methods for sampling and analysis that are appropriate for the Central Texas Hill Country ecoregion. This project provides not only the baseline biological data for future reference and comparison, but also a model for future monitoring projects.

Concurrent with the Bioassessment Pilot Project, the City of Austin developed and implemented protocols for the monthly monitoring of surface populations of the Barton Springs salamander and their springs habitat. Once again, these data have provided a wealth of biological information concerning the range, distribution, and population dynamics of the surface population, along with assessments of the general biota and habitat. The detail of these data is in sharp contrast to previous studies that provide only anecdotal accounts of salamander distributions and ranges, aquatic macrophytes, and available habitat. As development increases in the Recharge and Contributing Zones of the aquifer, the biological monitoring protocols and tools are in place to assess and evaluate the impacts of changing watershed and water quality conditions, as well as to provide necessary information for watershed managers and policymakers.

5.0 MODEL AND MASTERPLAN SUMMARIES

5.1 INTRODUCTION

The first of the two modeling studies focused on surface water hydrology and water quality in Barton Creek. This project was initiated by the adoption of the City Manager Barton Creek Policy Definition Report in 1988 and subsequent funding by Council in 1990. The majority of the work on this model was completed by ERM staff and the UT Center for Research in Water Resources (CRWR). However, contributions were made in the early stages of the project through a consultant Technical Assistance contract with Espey, Huston, and Associates including sub-contract agreements with CRWR, Tom Loomis and Associates, and Dr. Loren Ross. The results of this effort are documented in the Barton Creek Surface Water Modeling Study (COA 1997 Draft). However, a brief summary of the project including pertinent conclusions and recommendations is provided herein.

The second modeling study, focusing on modeling the hydrology and water quality of the BSEA was initiated by City Council in 1994 through an interlocal agreement with CRWR. The need for this project was defined during work on the surface water model due to the absence of an adequate routine in the selected public domain surface water model which could be used to simulate movement of water and transport of pollutants in a Karst aquifer interacting with a recharging creek. The results of this project are documented in CRWR Technical Report 269 - A Parsimonious Model for Simulation of Flow and Transport in a Karst Aquifer, November 1996 (Barrett, 1996). As with the surface water model, a brief summary of the project, conclusions, and recommendations are provided herein.

The Barton Springs Contributing Zone Retrofit Masterplan Study was conducted through a consultant contract with Santos, Loomis and Associates and subcontractors. The study examined opportunities for improving water quality in contributing watersheds to the Barton Springs Segment of the Edwards Aquifer (Barton Springs Zone - BSZ). The contractors performed a review of water quality conditions in the BSZ and provided an assessment of current pollutant loading sources including urban runoff, channel erosion in general terms, septic systems, effluent irrigation, and rangeland. The study also provided an analysis of structural and non-structural retrofit strategies in water quality improvement. Proposed sites and cost estimates for retrofit implementation were also provided.

5.2 BARTON SPRINGS SURFACE WATER MODEL

Several modeling tools were proposed for investigating the effects of land use changes on water quality, and this report describes the efforts towards application of a predictive model for water quantity and quality in Barton Creek. The general purpose of the modeling effort was to develop a tool capable of explicit representation of the physical processes governing water quantity and quality in the Barton Creek Watershed. The focus of this modeling effort was the application of the industry standard public domain Stormwater Management Model (SWMM) to the Barton Creek Watershed. Due to SWMM ground water routine limitations, only the portion of the watershed above the Recharge Zone was simulated.

Ideally, the results from the SWMM were to be used as simulation input to the ground water model in order to predict the impact to Barton Springs discharge water quality under a variety of land use scenarios. Due to the complexity of the system modeled and the limitations of the available model formulations, water quality was not predicted well. A statistical formulation did allow simulation of historical conditions. Water quantity, however, may be simulated well enough by SWMM to provide a basis for input scenarios to the ground water model using land use based mean concentrations from the COA Storm Water Monitoring Program. This use of the model is under investigation in association with the Drainage Utility City-wide Masterplan

5.2.1 Data Analysis Supporting Surface Water Quality Modeling Efforts

One of the major contributions of the surface water model study was the analysis of data from both the USGS stations located in the watershed and that provided by the City of Austin Storm Water Monitoring Program (Plate 6). A significant amount of information was provided on hydrology and water quality in Barton Creek from the summary of these data.

In the analysis of USGS discharge gaging station data, flows in Barton Creek were separated into baseflow volumes and direct runoff volumes. Above the Recharge Zone, more than three-quarters of the flow volume was baseflow (Loomis, 1995). This fraction decrease over the Recharge Zone as flows contributed to aquifer recharge. On the basis of baseflow volume differences between the Lost Creek and Loop 360 gaging stations, it is estimated that for Lost Creek flows of less than 20 to 30 cfs, all of the flow is lost to recharge. The recharge rate remains constant at about 30 cfs for channel discharges ranging from 30 to 130 cfs. For channel flows at Lost Creek in excess of 130 cfs, the recharge rate is about 23 percent of the Lost Creek discharge. All of these estimates include only the recharge occurring between these two stations.

Stormwater quality from individual rainfall events is quite variable from storm to storm, through time for a given event, from one constituent to another, and from one site to another. The USGS/City of Austin joint monitoring program provides data for evaluating water quality along the mainstem of Barton Creek. Available water quality data for three stations along Barton Creek were analyzed and are presented in summary form in Table 5.1. Mean values for most of the constituents are higher during storm flow conditions than for baseflow conditions. TSS, which is one of the most widely used indicators of stormwater impacts, has an average concentration which is an order of magnitude larger under storm flow conditions when compared with baseflow conditions. Both the storm flow mean TSS concentration and its variability increase for downstream stations along the Creek. The storm flow mean TSS concentration at Loop 360 is more than double that at Highway 71 and Lost Creek stations, possibly reflecting the impacts of land use changes in the lower portions of the watershed.

Stormflow and baseflow data from the USGS stations was evaluated prior to use in model calibrations. Of the water quality constituents which are correlated with discharge rate in stormflow data, all except total lead (TPb) have average concentrations which are greater at Loop 360 than at the other monitoring stations. One explanation of these increases is the

Table 5.1
Barton Creek Water Quality Summary Statistics

BASEFLOW CONDITIONS

Constituent	Hwy 71 (08155200)				Lost Creek Blvd. (08155240)				Loop 360 (08155300)			
	Count	Period of Record	Mean	Std. Dev.	Count	Period of Record	Mean	Std. Dev.	Count	Period of Record	Mean	Std. Dev.
Flow (cfs)	69	1978-1996	35	83	30	1989-1996	72	166	30	1978-1996	61	110
TSS (mg/L)	68	1978-1996	4	7	29	1988-1995	4	4	27	1979-1995	4	5
Dis. TDS (mg/L)	35	1978-1994	257	30	19	1988-1994	396	220	19	1979-1983	252	32
BOD5 (mg/L)	68	1978-1996	0.55	0.40	30	1989-1996	0.48	0.32	27	1979-1995	0.46	0.32
TOC (mg/L)	26	1978-1996	2.93	2.29	11	1993-1996	2.63	1.30	3	1994-1995	4.63	3.13
Fecal Coliform (col/100mL)	69	1978-1996	1571	8911	31	1988-1996	126	289	27	1979-1995	387	1762
Fecal Strep (col/100mL)	69	1978-1996	3417	11580	31	1988-1996	243	499	27	1979-1995	336	1048
TP (mg/L)	70	1978-1996	0.02	0.02	31	1988-1996	0.03	0.08	27	1979-1995	0.01	0.01
NO3/2-N (mg/L)	51	1978-1995	0.12	0.12	25	1988-1996	0.18	0.16	25	1979-1995	0.18	0.14
NH3-N (mg/L)	35	1978-1992	0.02	0.02	15	1988-1992	0.02	0.02	22	1979-1992	0.02	0.02
TKN (mg/L)	69	1978-1996	0.25	0.15	30	1988-1996	0.24	0.08	27	1979-1995	0.44	0.81
Dis. Copper (ug/L)	34	1978-1994	6.71	4.58	18	1989-1994	9.00	2.91	16	1979-1993	5.06	4.58
Dis. Iron (ug/L)	34	1978-1994	8.00	8.51	18	1989-1994	5.33	3.05	18	1979-1993	12.11	22.24
Dis. Lead (ug/L)	34	1978-1994	7.32	5.38	19	1989-1996	9.32	3.93	17	1979-1993	5.18	4.43
Tot. Lead (ug/L)	47	1991-1996	2.43	6.75	22	1991-1995	1.32	0.89	10	1979-1995	1.10	0.32
Dis. Zinc (ug/L)	34	1978-1994	7.26	9.81	18	1989-1994	7.72	13.62	17	1979-1993	17.88	52.47

STORMFLOW CONDITIONS

Constituent	Hwy 71 (08155200)				Lost Creek Blvd. (08155240)				Loop 360 (08155300)			
	Count	Period of Record	Mean	Std. Dev.	Count	Period of Record	Mean	Std. Dev.	Count	Period of Record	Mean	Std. Dev.
Flow (cfs)	71	1978-1995	1128	2332	82	1989-1995	1203	2379	143	1981-1995	1745	2646
TSS (mg/L)	68	1978-1995	279	327	71	1989-1995	223	305	114	1979-1995	515	614
Dis. TDS (mg/L)	8	1978-1995	179	62	6	1989-1995	225	50	41	1979-1995	184	61
BOD5 (mg/L)	68	1978-1995	3.42	3.23	73	1994-1995	3.05	3.66	123	1979-1995	3.53	2.99
TOC (mg/L)	34	1993-1995	9.55	10.00	34	1989-1995	8.10	9.22	27	1994-1995	12.09	7.71
Fecal Coliform (col/100mL)	66	1978-1995	15440	18766	72	1989-1995	9978	11274	119	1979-1995	19495	20366
Fecal Strep (col/100mL)	66	1978-1995	28295	33050	72	1989-1995	17351	19892	119	1979-1995	26386	25066
TP (mg/L)	67	1978-1995	0.08	0.09	74	1989-1995	0.11	0.16	131	1979-1995	0.15	0.17
NO3/2-N (mg/L)	60	1978-1995	0.17	0.20	74	1989-1995	0.22	0.14	131	1979-1995	0.33	0.22
NH3-N (mg/L)	27	1978-1992	0.05	0.06	35	1989-1995	0.05	0.05	97	1979-1993	0.07	0.08
TKN (mg/L)	67	1978-1995	0.77	0.64	74	1989-1995	0.67	0.72	133	1979-1995	1.26	1.58
Dis. Copper (ug/L)	6	1978-1995	4.00	4.69	6	1989-1995	5.50	4.93	41	1979-1995	3.95	4.31
Dis. Iron (ug/L)	6	1978-1995	30.67	22.50	6	1989-1995	14.83	10.61	41	1979-1995	24.44	25.34
Dis. Lead (ug/L)	6	1978-1995	6.50	7.37	6	1989-1995	5.50	4.93	41	1979-1995	3.83	3.78
Tot. Lead (ug/L)	60	1978-1995	11.28	22.65	63	1990-1985	5.29	5.83	51	1979-1995	8.33	8.68
Dis. Zinc (ug/L)	6	1978-1995	5.33	2.88	6	1989-1995	7.33	5.61	41	1979-1995	10.07	10.81

Source: USGS Data used in Barton Creek Surface Water Model Report (COA 1997 Draft) greater amount of impervious cover at the lower end of the Barton Creek Watershed. In addition, BOD_5, TOC, FCOL, FSTR, and total nitrogen have average concentrations which are one to two orders of magnitude larger during direct runoff conditions. Further, the mean TOC concentration at Loop 360 more than doubles that at Highway 71 and Lost Creek under storm flow conditions. The average TDS concentration is larger for baseflow than for storm flow conditions at all three stations, with greatest concentrations at the Lost Creek station. Correlation analysis shows that TSS, BOD_5, TOC, TKN, FCOL, FSTR, TP and TPB all increase with flowrate in stormflow conditions, while only NO_2+NO_3 is inversely related to flowrate in storm flow conditions. The other water quality parameters are insignificantly correlated to the runoff magnitude. In baseflow data, only NO_2+NO_3 - N was correlated inversely to flow rate. Details of the data analyses used in support of the surface water model effort are presented in a separate document (City of Austin, 1997).

5.2.2 SWMM Model Application

The EPA SWMM was identified as having the greatest flexibility and potential for application as a stormwater quantity and quality simulation tool for the large and complex Barton Creek Watershed. In application of the SWMM model to the Barton Creek Watershed, only four of the simulation model blocks were utilized: the runoff, transport, statistics, and rain blocks. The Green and Ampt infiltration model was used, but it was found that the overall performance of the model was not very sensitive to this choice. The subsurface flow system was modeled as a linear reservoir. Flow rate from the saturated ground water zone to the stream channel was based on head differences between the aquifer and channel bottom.

The *Hydrolog* Software package which was developed as part of this project is a system for hydrologic and stormwater quality analyses. This package simplifies the many analyses which were required to calibrate watershed models such as SWMM, and provided a set of tools for analysis of stormwater runoff data.

Extensive rainfall and streamflow data were available through the City of Austin and the USGS monitoring programs. These data cover single land use watersheds and the Barton Creek Watershed at three stations. Because rainfall is not uniform over large areas, there was always uncertainty as to how the recorded rainfall reflects watershed average values. Correlation analysis suggested that available records were adequate for most conditions, even over the upper reaches of the Barton Creek Watershed for most of the year. Summer months did not calibrate as well due to typically localized rainfall patterns. This limits the available time periods for long term validation using SWMM or any other watershed simulation. Rainfall distribution and quality of rainfall data from FEWS stations posed a major calibration problem with large scale watershed modeling of Barton Creek.

Variables and parameters used for modeling flow in the Barton Creek Watershed were primarily physically based. Most parameters were estimated before the calibration process begins through physical equations and measured parameters. In some respects, this simplified calibration because there were fewer model parameters to adjust in order to obtain a better fit to the observed data. The only parameters which were modified for the Barton Creek calibrations were the effective watershed width and the baseflow intensity parameter. In addition, these were modified for all watersheds uniformly so that their values were not changed for each subcatchment independently. The single land use watersheds did not have a subsurface flow component, so many of the flow parameters in the single land use watershed model were not used. Fewer subcatchments and parameters to consider were also present in the single land use watershed models, and the effective watershed width remained a sensitive variable.

Applications showed that the SWMM model can be adequately calibrated for representation of the hydrology of a single land use site and for the Barton Creek Watershed (above the Recharge Zone). Both single event and long-term periods can be simulated. The existing SWMM formulation is not able to simulate water loss from the Creek over the Recharge Zone, so the model cannot be used to simulate flow quantity at the Loop 360 station.

Simulating stormwater quality proved to be more difficult than that of simulating stormwater quantity. The buildup model used in SWMM did not give results consistent with observed data. In addition, no other public domain model was identified which could adequately replace those available within SWMM. Therefore, the model, if applied to a single land use watershed, or any more complex watershed, would not be represent the available constituent load (buildup) at the beginning of a runoff event. Thus the washoff load and concentrations also remain uncertain. However, if the buildup could be predicted, the washoff model based on total storm runoff appeared to adequately represent the monitoring data.

For large storm events, much of the sediment load in Barton Creek was determined to be derived from erosion of the channel, rather than from watershed surface stormwater runoff. The potential load from erosion increased for locations further down the watershed.

The overall conclusion from the investigation of the single land use data is that a model does not exist that can adequately predict the accumulated stormwater load on a watershed at the beginning of a runoff event, nor the initial constituent concentration. The model does do a better job of representing the washoff processes. Thus, SWMM may be a useful model for simulating single storm events, but not a continuous series of events.

5.2.3 Statistical Model Application

Statistical regression analysis provided empirical models for prediction of water quality in Barton Creek as a function of location, season, time period (construction), existing flow conditions, and antecedent flow conditions. Compared to the baseflow model, the models for storm flow conditions have greater predictive power.

Application of the statistical regression water quality model with a measured or simulated discharge hydrograph will provide useful estimates for Barton Creek water quality at the three monitoring stations. But it is difficult to extrapolate the model form to address questions associated with impacts of land use changes on water quality. For the most part, baseflow water quality concentrations were not found to be impacted by construction activities in the Austin area during the period of 1983 - 1986. On the other hand, during storm flow conditions, the water quality concentrations in Austin area creeks showed an increase during this period of active construction. In particular, the average TSS concentration increased by 550 mg/L.

A substantial amount of variability remains in the storm and baseflow water quality data after statistically accounting for flow rate, site, season changes, and prior flow rates. Additional research might provide further insight into the source of this variability.

5.2.4 Conclusions

The following conclusions derived from a variety of data analyses and simulations are provided in summary of the Surface Water Modeling project:

- From literature review and recent applications, SWMM and HSPF (Hydrological Simulation Program - Fortran) are the most generally applicable detailed public domain models for simulation of stormwater quantity and quality for single and multiple events.

- Application of SWMM to single land use watersheds was successful for estimation of both quantity and stormwater quality loads for single event simulations.

- Single land use water quality data appears to follow the theoretical washoff process (used by most Non-Point Source water quality models) for certain constituents including TSS. However, prediction of initial concentrations through a constituent buildup process is not supported by the empirical data. Further, for certain constituents, the concentrations are greater on the rising limb of the hydrograph than on the falling limb, and a functional relationship between flow and concentration is not applicable. Therefore, simulation of multiple events on single land use watersheds cannot be performed.

- Deterministic models such as the buildup/washoff relationships lack the capability of predicting multiple-event (consecutive) pollutographs in the single land use data set developed by the COA Storm Water Monitoring Program.

- Prediction of total annual loads using buildup and washoff with calibration may be possible. However, equivalent methods are available for planning levels of analysis which are less labor intensive than application of SWMM modeling. The planning level loading model will allow prediction of cumulative loads from developed areas as a function of land use and impervious cover changes.

- The COA/USGS stormwater monitoring program is one of the most intensive in the country in terms of the number of locations monitored and samples taken. For events on single land use watersheds, there are a large number of events with sufficient data to adequately characterize the pollutograph for calibration purposes. However, despite the extensive database contributed to this study, the stormwater monitoring program on Barton Creek has provided only a small number of storms with sufficient data for characterization of the consecutive pollutographs for model calibration purposes.

- The SWMM model was developed with sufficient flexibility to represent many important features in the hydrologic cycle. However, channel losses such as occur over the Recharge Zone of the Edwards aquifer were not represented in a realistic fashion.

- For the Barton Creek Watershed above the Recharge Zone, the SWMM model was adequately calibrated to simulate observed creek flows over periods of short duration and was partially calibrated to simulate flows over periods of long duration. Significant anomalies exist in the flow gage data, making long duration calibrations problematic.

- Stormwater quality was evaluated through measured TSS concentrations. Given the single land use monitoring data, watershed derived TSS load from each subcatchment of the Barton Creek Watershed was estimated, and thus the expected loads at the monitoring stations along the Creek were estimated. However, the observed TSS loads greatly exceeded the estimated loads because of channel derived TSS.

- While there are few records with sufficient data to characterize the stormwater quality pollutograph for Barton Creek for SWMM calibration, there are sufficient data to apply statistical regression techniques to develop a statistical model for simulating historical stormwater quality. Therefore, a statistical model was developed with some limited predictive capabilities for stormwater quality in Barton Creek under existing land use conditions.

- Pollutographs from single land use stormwater quality monitoring were analyzed in terms of buildup and washoff models. Washoff data were used to develop predictive models for the washoff pollutograph for certain constituents including TSS. This model met with limited success when compared with empirical data because the initial concentrations remained uncertain.

- From the data provided by the ERM stormwater quality monitoring program, stormwater pollutant loads were more sensitive to changes in stormwater quantity than concentration. Thus, land use changes that increased stormwater quantity (runoff) are especially significant in increasing constituent loads.

5.2.5 Recommendations

The following recommendations are provided in summary from the Barton Creek Surface Water Model Study in the areas of model applications, regulatory and development review, data collection, and further research:

5.2.5.1 Model Applications

- Using the developed model framework, the Barton Creek SWMM Model can accurately predict flow quantities above the Recharge Zone. Therefore, the calibrated model can be used to develop flow inputs to the Barton Springs/Edwards Aquifer ground water model developed under a contract between the City of Austin and CRWR. The calibrated SWMM model can be used to predict changes in baseflow and direct runoff quantities in Barton Creek resulting from changes in impervious cover for various development and regulatory scenarios. This will allow the prediction of urban development effects on water levels in the aquifer and discharge rates at Barton Springs.

- Analysis of water quality data demonstrated the relative importance of channel derived load. Much of the concern about the viability of the Barton Springs salamander is centered on the effects of increased suspended solids loads in the Creek and Springs. Approximately 50 percent of the suspended solids load in the lower segments of the Creek is estimated to originate from bank erosion.

- The Barton Creek Model could be used to predict the changes in flow rates which will accompany increased urban development in the watershed. The model can, with some modifications, be used to assess the effects of various BMP's on flow rates during runoff events.

- Through this modeling effort ERM has developed a familiarity with the operation, capabilities and limitations of SWMM. Because all of the available models have unique limitations and capabilities, it is recommended that the City support the use of SWMM in the Barton Creek Watershed due to its familiarity and flexibility. The recommended uses of SWMM include the evaluation of various BMP's using the storage/treatment block in addition to the four blocks used in this study. The storage/treatment block simulates the effect upon flow quantity and quality of capture and residence processes occurring in structural water quality or quantity control devices. SWMM should also be used to provide guidance in site selection and planning for single land use flow monitoring.

5.2.5.2 Regulatory and Development Review

- City of Austin flood control regulations should be revised to account for Barton Creek to pollutant loading due to channel scour, as documented in this study. Current regulations, which are based on limiting the peak discharge to predevelopment conditions, may have unintended consequences on flow rates in creeks downstream of discharge points. Depending on the relative position of the site and other factors, stormwater detention facilities constructed to City standards may increase storm flow rates in the main creek channel downstream of the site compared to developed conditions with no controls in place. The Barton Creek Model should be used to evaluate the effectiveness of current regulations and predict the impacts of proposed changes to these rules.

- Infiltration practices should be promoted as an effective water quality BMP based on the following conclusions:
    - ◊ Analysis of data from single land use watersheds indicate that the amount of impervious cover has a greater impact on stormwater loads than land use classification.
    - ◊ Peak flows and sustained velocities have a dominant impact on water quality due to channel scour and bank erosion.
    - ◊ The recreational uses of Barton Creek are dependent on the maintenance of a healthy baseflow.
    - ◊ Promoting baseflow in Barton Creek will help maintain the quality of water recharged to the BSEA.

Therefore, promoting infiltration practices through the City's water quality control standards is recommended to reduce runoff entering the channel, decrease channel scour and water quality impacts, and assure that baseflow quantity will not be reduced.

5.2.5.3 Data Collection

- To address the potential problems associated with channel derived suspended solids the City should implement a monitoring program to document current rates of bank erosion and channel scour. Additional empirical data including critical stream velocity producing erosion will be necessary for the design of stormwater controls system.

- The accuracy of the Barton Creek Model is limited by a lack of accurate knowledge of rainfall distribution and evaporation rates. Continuously recording rain gages should be installed upstream of Highway 71 near the border of the City's ETJ to better document rainfall rates and volumes. The City should install a pan evaporation monitoring site to provide a backup source of data to the National Weather Service.

- A continuous flow gauge should be installed just upstream of Barton Springs Pool. The gage design should insure accurate measurement of recharge volumes including ground water discharge from the Edwards Aquifer to Barton Creek during periods of high water levels in the aquifer. In addition, the gauge should provide a station for water quality measurements downstream of all development. Data from this site will be needed for model calibration if SWMM is modified to include channel losses and ground water recharge.

- To better understand the processes controlling water quality in Barton Creek, the frequency of sampling should be increased during storm events. In addition, the duration of sampling should define the transition from direct runoff to baseflow water quality. An automated station similar to that used in the City of Austin Storm Water Monitoring Program should be maintained in Barton Creek to obtain this high resolution data at the least cost to the City. Additionally, the FEWS gages in the watershed with depth monitoring capabilities should be converted to flow rate monitoring by developing accurate rating curves. This will allow the transition to baseflow to be characterized in greater detail.

- ERM monitoring of rainfall water quality should be expanded to document the possible differences between urban and rural rainfall quality. This monitoring will help establish a relationship between rainfall and runoff water quality.

5.2.5.4 Additional Research

- A study should be initiated to evaluate channel stability and sediment transport in Barton Creek. The study should be supported by the ongoing City-wide Master Plan because it will complement the planned needs assessment for erosion control scheduled for Non-Urban watersheds within the next several years.

- Beginning with SWMM version 4.26, the model has been modified to simulate channel losses. The most recent version should be investigated, with the additional data provided by the recommended monitoring gauge above Barton Springs, to see if they can evaluate channel losses over the Recharge Zone.

- The SWMM model should be modified to incorporate the predictive model for the stormwater washoff pollutograph with variable RCOEF and combined with a stochastic generator for selection of initial concentrations. Thus the model could provide a tool for generating realistic multiple event stormwater loads for design and evaluation of BMP's. Such a representation would also be adequate for simulation of yearly loads, and could provide a more realistic representation for the input loads to BMP's.

- A statistical cluster analysis should be performed using all 48 water quality constituents currently measured. This analysis will lead to a grouping of constituents which show similar water quality behavior. From defining statistically prioritized groupings representative indicator constituents for monitoring can be selected, thereby reducing the number of analyses performed on a routine basis.

- It has been suggested that the inability of the model to simulate water quality in single land use watersheds was related to the absence of flow and rainfall data between storm events. Once such data is obtained the model should be revisited to determine the validity of the buildup algorithm.

5.3 BARTON SPRINGS EDWARDS AQUIFER GROUND WATER MODEL

The goal of this study was to develop a regulatory tool to assess the effectiveness of various management strategies for preventing the degradation of aquifer water quality and availability. Three important tasks were required to accomplish this goal. A parsimonious model was formulated with the ability to 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 estimated. This included methods to estimate current and future nitrogen loads from septic systems and rainfall. 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 reductions in the quantity and quality of water recharged to the aquifer due to varying degrees of development.

Recommendations for changes in the monitoring programs were made based on the results of the model. 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.

At the present time, no attempt was made to numerically correlate the results from methods of monitoring described in Section 2 with the long term simulations completed in this modeling study. However, the conclusions reached from datalogger recordings and grab sampling at springs are consistent with that predicted by the groundwater model effort. Because modeling of transients in a Karst aquifer system is not economical, the cumulative impact of these events will have to be evaluated on a qualitative basis.

5.3.1 Model Development

This study developed a new type of lumped parameter model for the BSEA. The aquifer was divided into five cells corresponding to the five major creeks supplying recharge to the aquifer. Each of the cells was treated as a tank with a single well used to characterize conditions in the cell. This model differed from previous models in that it allowed properties within the cell to vary with water elevation. Because movement of water within cells was not considered, the model retained the lack of a spatial dimension characteristic of lumped parameter models. The model was 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 demonstrated its accuracy. This simple representation of the hydrologic system produced accurate results with fewer data requirements and calibration parameters than traditional ground water models.

Verification of the transport capability of the model was conducted using total nitrogen. This constituent originally was 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. Nevertheless, nitrogen was still an attractive choice for transport modeling because of the concern about the effect of additional nutrient sources in the Recharge Zone. In addition, nitrogen concentrations were 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.

5.3.2 Conclusions

The following conclusions are summarized from the Parsimonious Model for Simulation of Flow and Transport in a Karst Aquifer (Barrett, 1996):

- The potential effects of urban development in the areas supplying recharge to the aquifer were investigated using the model. The projected changes in the hydrology of the creeks were estimated using data from other creeks in more developed parts of the Austin area lacking significant numbers of stormwater runoff controls.

- Development simulated in the model 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 be extended periods of baseflow so that the average minimum spring discharge remained unchanged.

- Model simulations with varying levels of development indicated that unless urban development dramatically increased there is little danger that Barton Springs would cease to flow under normal rainfall conditions. Changes in the hydrology of the creeks caused by urbanization tended 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 water 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.

- During the drought of the 1950's, discharge of the springs was reduced from an average of 50 cfs to less than 10 cfs. Continued population growth and reliance on the aquifer for drinking water may result in even greater reduction when a drought of this severity recurs. Low spring flow may pose a serious threat to the Barton Springs Salamander and affect the operation of Barton Springs Pool which draws over 300,000 swimmers annually. Evaluation of this potential problem is an appropriate use of this ground water model.

- 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, but their effect in the aquifer was not evaluated in this study. These pollutants 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.

- Increased urbanization will likely reduce the quality of the water recharged to the aquifer. Only the effect of urbanization on nitrogen concentrations was modeled as part of this research. A level of intense development (45 percent impervious cover), was estimated to raise the predicted nitrogen concentration at Barton Springs from about 1.5 mg/L to approximately 3.5 mg/L, an increase of approximately 130 percent, Using a moderate level of development (20 percent impervious cover), the predicted nitrogen concentrations at Barton Springs increased from 1.5 mg/L to 1.8 mg/L, an increase of approximately 20 percent. Average concentrations in the aquifer are predicted to experience similar percentage increases. The greatest impact may be on Barton Springs Pool and Town Lake, where the increased nutrient supply may promote the growth of algae and euthrophication.

- 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. 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 minimal ground water is used in this area. Changes in water quality in the Pool will probably be larger during recharge events compared to the average changes predicted by the ground water 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 with 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 more evaluation.

- In addition to water quality changes at the pool, increase in peak flow frequency will correspondingly increase pool closures due to overtopping of the dam.

5.3.3 Recommendations

The following recommendations are summarized from the ground water model report in the areas of future surface water monitoring , ground water monitoring, and rulemaking.

5.3.3.1 Surface Water Monitoring Recommendations

- Install a monitoring site on Barton Creek just upstream from Barton Springs Pool to determine the relationship between the creek and aquifer between Loop 360 and Barton Springs Pool. The flow behavior of this stretch of the creek is critical for accurate calibration of the ground water model. In addition, this is the most highly developed area in the Barton Creek Watershed and presumably has the lowest water quality. A stream monitoring station should be installed just above the Barton Springs Pool or in the creek bypass. Water quantity measurements at this site would also demonstrate the effect of intense development on the water quality in 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 segmentation would allow a more rapid increase in spring discharge and create the short term variability in water quality observed during recharge events and yield calibration parameters which may assume more physically realistic values for cells near the springs.

- Move Williamson Creek monitoring site to the upstream edge of the Recharge Zone. The ground water model was developed and calibrated using flow data from Williamson Creek at Highway 290, located at the upstream edge of the Recharge Zone.

The monitoring station at this site was discontinued and replaced with a station at Brushy Creek Road, located approximately halfway across the Recharge Zone. This new location should not affect water quality inputs to the model, but will result in underestimating water quantity because much of the flow is lost to recharge before reaching the gaging station. Because Williamson Creek contributes the least amount of recharge of any of the creeks, errors caused by using data from the existing station will not be large; however, moving the site as proposed would introduce less uncertainty in model calibration.

- Install temporary monitoring sites on Little Bear Creek to better establish water quality and recharge behavior. Little data currently exists for flow and recharge for Little Bear Creek. It is typically assumed to have the same characteristics as Bear Creek; however, the two watersheds are different in area of recharge and quality of recharge.

- Determine recharge characteristics for specific stream segments within the Recharge Zone because the current model cannot include the effects of storm water runoff from the Recharge Zone. In order to modify the model to accomplish this, both a calibrated surface water runoff model and more detailed local information on recharge rates in specific segments of the creek would be necessary.

5.3.2.2 Ground Water Monitoring Recommendations

- Estimate Barton Springs discharge from a well located farther away from the pool. The current estimates from USGS monitoring well YD-58-42-903 are flawed because they are highly dependent on pool levels. Therefore, draining the pool for maintenance is an artificial factor in estimating of spring flows. Well 58-42-915 is a suggested alternative well near the intersection of Rabb Road and Rundell Place. More accurate estimates of spring flow would increase the accuracy of the model by providing a wider range of water levels to relate to flow.

- Monitor daily water levels in a well located near the intersection of Manchaca and Slaughter Lane. Levels are not well established in this area because a well with daily water level measurements is not currently located in this cell. The BS/EACD monitors a well near Circle C development; however, this well does not appear to be hydraulically connected to the rest of the aquifer judging from water level records. The optimum location for a new well to suit this purpose is near the intersection of Manchaca Road and Slaughter Lane.

- Evaluate the persistent high nitrate-nitrogen concentrations in the well in the Slaughter Creek watershed (58-50-406). Attempts should be made to determine if the cause is a localized source or a poorly constructed/damaged well casing. These measurements are accurate, additional planning may be needed to prevent reduction of drinking water quality in Sunset Valley, located immediately down gradient from this area.

- Increase frequency of water quality sampling in all BSEA wells in the RZ and CZ and at Barton Springs in order to identify changes in water quality at the earliest possible time. Because of natural variability, the number of samples necessary to statistically support water quality degradation is large. Based on historical data variations, frequency for future monitoring should be calculated.

- Develop data on flow paths, travel times, and other pollutant transport properties for future use in a more detailed ground water model. This will help to further define spatial resolution of the model and to allow the model to simulate impacts of spills and point sources of pollution throughout the watersheds. Dye tracing studies as initiated between the ERM and BS/EACD are a common method for obtaining this information.

5.3.2.3 Development Review and Planning Recommendations

- In development review, alter the calibrated model to investigate the effects of potential impacts to the hydrologic system. Modify the physically based parameters of the model to explore the expected effects of a specific development.
- Use various storm water control strategies with the model to determine their expected overall effectiveness for achieving goals such as non-degradation or no impairment of beneficial uses. The chief concern at this stage of the model usage is the reliability and

accuracy of the model under conditions other than those for which the model was calibrated.

- In the case of a surface water model, investigate the potential impact of full development in the Barton Creek Watershed. 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 estimating the effect of development and the efficiency of the proposed control strategies. Therefore, it must be recognized that there will always be a degree of uncertainty (probably large) about whether the right policies have been implemented.

5.4 BARTON SPRINGS ZONE RETROFIT MASTER PLAN STUDY SUMMARY

The following summarizes the water quality assessment, retrofit analysis, the findings, and recommendations provided in the Barton Springs Zone Retrofit masterplan.

5.4.1 Water Quality Assessment

Although the assessment of current conditions indicated that water quality was "excellent", observable or measurable degradation in the BSZ was determined to include "statistically discernible increases in mean constituent concentrations in stormflow and baseflow at creek locations in the more developed basins, pockets of algae growth, apparent staining of rocks in areas draining roadways, several significant erosion sites, unusual accumulations of trash and debris, and sedimentation and toxics accumulations measured in some wells". (Loomis, 1996) Primarily TSS and TN were used as indicators of water quality in the BSZ retrofit masterplan.

The sources of contamination in the BSZ may include urban runoff, in-channel erosion, construction related sediment, septic systems, effluent irrigation, and rangeland degradation. The link made between these processes and the observed data were based on some preliminary estimations which have since been refined through targeted studies such as those discussed in previous sections of this report. For example, in conducting the ground water model, the researchers proposed a nitrogen balance which apportioned the source of this constituent differently from the BSZ retrofit masterplan. This was due to additional data obtained on the number of septic systems in the BSZ from the BS/EACD, additional data on the nitrogen concentration of rainfall in the Austin area obtained through the COA Stormwater Monitoring Program, and a refinement of the assumptions for septic tank effluent concentration of nitrogen obtained from the ATCHHSD.

5.4.2 Water Quality Retrofit Evaluation

Implementation of major structural retrofits was proposed at 26 sites yielding an estimated 4.5 percent reduction in TSS loading and 3.1 percent reduction in TN loading to the BSZ at a cost of $11 million. Rangeland management of 15 percent of the undeveloped forested area estimated comparable benefits although cost estimates were not provided. Smaller, site specific structural controls were found to provide less of an impact than regional controls. However, non-structural controls researched including regulatory and public education approaches, were estimated to have a potential significant impact on minimizing degradation in the watersheds of the BSZ.

Structural water quality retrofits considered standard City of Austin sedimentation/sand filtration basins, retention-irrigation ponds, and wet pond/constructed wetlands. Based on capital cost and performance evaluations, retention-irrigation was the most effective technology. However, maintenance requirements for these systems were higher than others due to the mechanical components involved. Detention-irrigation was proposed at about 80 percent of the sites selected for regional structural controls. Inlet filters were examined for widespread use; however, it was determined that they were relatively ineffective in residential areas because nutrient removal is poor and the high TSS and trash removal efficiencies of the traps are unnecessary. Hot spot controls for toxics and non-conventional pollutant removal were examined and multi-chambered treatment train designs were proposed as more effective than standard oil/grit separators. Hazardous Material Containment Structures were evaluated by reviewing the 1993 study Risk Study and it was determined that cost and maintenance limited their use to only a few high risk locations.

Rainwater harvesting was also evaluated and found to be less cost effective than pond BMP's; however, retrofit of large numbers of roofs could result in meaningful gains especially in commercial settings. Channel stabilization/biorevetment was evaluated but was recommended in only a few isolated areas.

Non-structural controls such as public information and education programs, rangeland management, and regulatory actions were evaluated as retrofit options. Continuation of community education programs was recommended, with expansion to the BSZ. However, numerical removal of pollutants cannot be correlated to public education efforts. Rangeland management improvement was found to provide an effective method to improve water quality as long as technical support and financial incentives to ranchers was provided.

5.4.3 Conclusions

In brief, the following conclusions were proposed in the retrofit masterplan based on the analyses provided:

- Development related changes in flow and constituent loads have occurred over predevelopment conditions throughout the BSZ with the largest occurring in Williamson Creek watershed.
- Urban processes have resulted in higher suspended solids from erosion and construction loads.
- Baseflow sources of nitrogen dominate the spring loading with septic tanks providing the dominant origin. This conclusion was based on a 0.5 mg/L assumption for rainfall TN whereas subsequent additional data indicated 1.5 mg/L to be a more appropriate estimate.
- Modeling of conventional septic systems indicated high migration rates to the aquifer; however, additional study has been undertaken by the Water and Wastewater Utility to verify this migration rate. Conclusions form this study are pending results from additional monitoring.

- Structural retrofits are limited in their effectiveness because of the relatively low percentage of TSS and TN loads which can be captured. However, combining these facilities with flood control structures may provide additional water quality benefits by reducing peak flows and capture of construction TSS loads.
- Public cooperation is necessary to effectively initiate a retrofit program in the BSZ.
- Given the magnitude of increase in loadings from predevelopment to developed conditions, retrofits cannot cost effectively reduce loads significantly.
- Site specific BMPs will also not be able to achieve regionally significant load reductions; however, combined with regional structural BMP's, watershed degradation can be minimized.
- When comparing the relative load reductions from a variety of water quality management strategies, the benefit per cost for rangeland management compared favorably to pond BMPs for TSS and less favorably for TN. Comparisons of other BMPs were complicated by the uncertainties involved in estimating load reductions.

Many of these recommendations have already been implemented by the Drainage Utility.

5.4.4 Recommendations

Recommendations from the consultant report include the following for the BSZ:

Policy Recommendations

- Implement the most cost effective water quality retrofit strategies including structural retrofits, septic system upgrades, public education, and rangeland management
- Continue strong water quality and detention requirements for new development because opportunities for meaningful retrofit are limited.
- Monitor construction sites closely for source control and BMP effectiveness.
- Target initial retrofits for implementation as soon as possible in order of cost effectiveness.
- Promote passive controls with little maintenance requirements and improve maintenance at all facilities.

- Encourage centralized sewers in septic areas or replacement with upgraded onsite systems.
- Require strong on-site source controls for new hot spot development in the BSZ.
- Continue and expand public education along with program evaluations to define the cost/benefits of the program.
- Initiate range conservation coordination with SCS, LCRA, TNRCC, and the ranching community to establish watershed restoration goals and implement a pilot study in rangeland management.

Monitoring Recommendations

- Continue golf study risk assessment for effluent irrigation and fertilizer application evaluations to determine threat to aquifer.
- Define existing water quality and creek degradation in the BSZ and the beneficial uses of the watersheds to increase public awareness of the uniqueness of the system.
- Quantify instream channel erosion and construction load reductions anticipated from structural water quality controls.
- Model baseflow reduction from impervious cover introduction and impact of large numbers of detention facilities on basin hydrology.
- Complete a detailed assessment of Williamson Creek.
- Refine septic system evaluation including sampling program and distribution of failure types in the watershed. Make better estimation of septic tank loads.
- Complete retrofit cost evaluation for replacing septic systems in the BSZ.
- Conduct intensive monitoring of stormflow and baseflow recession following significant event in Barton Creek or others in BSZ. Correlate dropping concentrations in baseflow with time or flow rate or both to understand the basin operation.
- Examine aquifer degradation threshold to define the limit of irreparable of significant degradation.
- Evaluate water quality control maintenance realities including current levels and costs for long term maintenance program and water quality impacts of maintenance failures.
- Evaluate recharge and springs flows through the BSEA system to better define recharge flows.

- Refine nitrogen budgeting in the Barton Springs system and reconcile nitrogen balance.
- Add septic system dominated watersheds to canyon study to determine increases in baseflow nitrogen from these systems.
- Perform additional modeling of golf courses and lawns to improve reliability of nitrogen balance.
- Assess pulse loadings and shape of probability distribution of loadings to determine affect on assessment of spatial and temporal averaging.
- Assess ERM water quality monitoring program; revise the program in order to better support ordinances, models , and tracking the health of the watershed.
- Support model development that quantifies load and concentration associated with development, load apportionment by source, effect of water quality controls, effect of septic tank usage, effect of rangeland management, effect of golf course management and effluent irrigation, and effect of subsurface processes in the aquifer.
- Perform water quality modeling capable of integrating development related loads, septic systems, and BMP implementation in prediction of changes in aquifer pollutant concentrations, creek water quality and flow patterns, ecology and morphology of riparian systems, and water well yield and quality.

Many of these monitoring recommendations have been implemented by the Drainage Utility and are addressed in Appendix G.

6.0 OVERVIEW OF REPORT CONCLUSIONS

The following sections summarize the most important conclusions derived from the ERM studies described in this report.

6.1 GROUND WATER PROGRAM CONCLUSIONS

- Flow measurements in tributaries of Barton Creek (and other watersheds) indicate that moderately dense urban development can have severe effects on base flow characteristics. While rural watersheds and those with low-density housing displayed well defined positive relationships between flow volume and drainage area, urban tributaries showed no relationship, positive or negative. This pattern is attributed to two factors. Impervious cover in urban watersheds prevents rain water infiltration from feeding shallow ground water tables which should then slowly discharge water into creeks as baseflow. In contrast, calculations show an urbanized tributary with effluent irrigation had a yield per acre nearly an order of magnitude greater than any rural or low-density watershed.

- Ground water quality is generally good in springs monitored in the Contributing Zone of the Barton Springs segment of the Edwards Aquifer within the Barton Creek Watershed. However, subtle impacts from human activities are present. Significant differences in ground water chemistry have been identified in springs located in urban versus rural areas of the Contributing Zone. Higher concentrations of the constituents total dissolved solids, total Kjeldahl nitrogen-nitrate, calcium, potassium, sodium, chloride, sulfate, alkalinity, and total organic carbon are found in urban ground water. Although these differences are statistically significant, ground water quality in urban areas remains good relative to drinking water standards. Elevated nitrate concentrations detected in the spring at Site 72/73 have also been detected in the pool downstream of the spring. This pool consistently has higher nitrate concentrations than any other pool site on Barton Creek. The probable source of the nitrate is the effluent holding ponds and effluent irrigation on a nearby golf course; although additional studies are necessary to confirm this conclusion.

- Of the five springs, Barton, Old Mill, Eliza, Cold, and Backdoor, Barton and Backdoor have the highest nitrate-nitrogen concentrations; 1.5 mg/L nitrate-nitrogen compared to 1.15 mg/L for the other springs. Data from in-situ multiprobe measurements from Barton, Old Mill, and Cold Springs show consistent differences in basic water chemistry. These differences are presumably related to differences in recharge areas, land use, and flow paths to each spring.

- Nutrient and metal concentrations in Barton Springs do not show clear time trends that appear related to urban development. Transient occurrences of tetrachloroethylene, heavy metals, including arsenic, cadmium, copper, lead, nickel, and zinc, and sediment show that anthropogenic sources are impacting Barton Springs. The presence of total petroleum hydrocarbons, heavy metals, and pesticides in other springs and wells also indicates that urban impacts to the aquifer are occurring. These effects are likely to increase as urbanization increases within the Recharge and Contributing Zones of Barton Springs.
  1) Many chemical constituents in Barton Springs show a relationship to discharge rate. Nitrate-nitrogen, total nitrogen, sodium, chloride, sulfate, magnesium, fluoride, total dissolved solids, and specific conductance are all inversely related to discharge. Dissolved oxygen, total suspended solids, and bacteria are all directly related to spring discharge rate.
  2) Nitrate nitrogen concentrations in Barton Springs are generally greatest during low discharge periods and still appear to be within background levels over the period of "useful" data. During low discharge (< 40 cfs) in 1981-82, nitrate nitrogen concentrations averaged 1.54 mg/L compared to 1.46 in 1995-96.

- Analysis eliminating wells with Glen Rose or Edwards "bad water line" signatures indicates that seven wells and Old Mill Spring appear to be subtly impacted by urbanization, as indicated by sulfate, chloride, and nitrate concentrations. Most impacted wells are in the northern end of the aquifer where urban development is the densest and oldest. It is possible that small volumes of water from adjacent aquifers richer in sulfate and chloride is giving three wells the urban signature identified in the

Bull Creek watershed, but the fact that two of these wells have had additional water quality problems suggests an urban source. Four wells consistently have nitrate concentrations greater than 1.5 mg/L.

- Barton Springs chemistry has several characteristic short term responses in chemical parameters following rain events. Specific conductance, and pH, typically decrease following rainfall whereas turbidity and dissolved oxygen typically increase. Temperature typically increases following rainfall, then decreases during fall, winter, and spring months or returns to pre-rain levels during summer months.

- Analysis of timing between rainfall in the Barton Creek Watershed and impacts in Barton Springs indicates an average lag time of approximately 14 hours with a range from 5 to 18 hours. Calculations for storm water velocities in the aquifer based on 14 hours migration time and recharge at various points along Barton Creek indicate stormwater velocities ranging from 329 to 1214 ft/hr, averaging 867 ft/hr. A grouping of shorter lag times of approximately six hours may represent responses to recharge in the Barton Hills area and indicate flow velocities for stormwater in the aquifer of 660 ft/hr. Isolated rainfall in the Williamson Creek watershed can generate very small impacts to Barton Springs with stormwater velocities estimated to range from 340 to 450 ft/hr.

- Recorded impacts on Barton Springs from numerous rain events indicated that the spring is most sensitive to events in Barton Creek. This implies that in the future Barton Springs will be more greatly affected by short and long term water quality conditions in Barton Creek than by other contributing creeks. However, chronic water quality problems in other recharging watersheds will also impact the springs and be a concern for those relying solely on the Edwards Aquifer for drinking water.

6.2 BARTON CREEK POOLS STUDY CONCLUSIONS

- Comparisons made between pools in this study illustrate some small but statistically significant spatial differences in water quality along Barton Creek's mainstem; however, temporal trends were shown to be insignificant by various statistical analyses over the period of record for this study.

- Surface water comparisons made among nine perennial pools over a five year period on the mainstem of Barton Creek indicate that the lower three study pools, all below Barton Creek Blvd. and along the most highly developed reach, are each impacted by either significantly higher nitrates, TDS, TSS, turbidity, or algal growth. The other six pools upstream of Barton Creek Blvd. show no significant degradation with the exception of significantly higher fecal coliform at the most upstream headwater pool. It is important to note that impacts to each of the lower three pools are localized and not ubiquitous along this lower reach of the creek. Water quality impacts seen at one study pool are remediated before reaching the next study pool, only to be replaced by other impacts related to local land use or construction activities.

- Baseflow water quality above Barton Creek Blvd. is fairly homogeneous, and the water chemistry along this reach of the mainstem has not deteriorated substantially since the 1988 Barton Creek Policy Definition Report was written. The baseflow water chemistry throughout the study area is still excellent compared to other urban streams contributing to Town Lake studied by the City 's Water Watchdog Program and to least-disturbed streams studied by TNRCC in the Central Texas Plateau ecoregion.

- The highest nitrogen and TDS concentrations are found in one pool located below Lost Creek Blvd. Bridge (Pool 8). The elevated nitrogen and TDS at this pool is a result of contributions from a spring, possibly enriched through leaks in effluent holding ponds or effluent irrigation in the area. Similar stable nitrogen isotope ratios and nitrogen concentrations link the spring and effluent, but continued investigations, including dye tracing, would be necessary to verify effluent as a source.

- The pool below Lost Creek Blvd. (Pool 8), downstream of residential and golf course land uses, is significantly higher than all other sites in percent cover of filamentous green algae, principally due to reoccurring *Cladophora* sp. blooms. Higher nitrates and conductivity correlate positively with higher filamentous algae at this site. From the documentation of one event, ERM staff have also observed that massive *Cladophora* blooms can result from nutrient surges resulting from accidental spills or mismanagement effluent irrigation.

- Significantly high turbidity is measured at two sites, one just below Barton Creek Blvd. (Pool 7) and one just above the Recharge Zone (Pool 9). The Recharge Zone site is also significantly higher in TSS. Intense local construction activity and adjacent upstream impoundments which trap and concentrate the fine sediments from construction sites are the only observable source for these elevated TSS concentrations. In general, higher TSS values were caused by an increase in mineral sediment load rather than organic sediment load as observed through VSS to TSS ratios.

- Fecal coliform is significantly higher at the most upstream rural site (Pool 1); however, bacteria counts are still very low there compared to other urban creeks and normally within safe limits for recreational contact. If fecal coliform to fecal streptococci rations are taken as adequate indicators, then fecal coliform is of an animal, not human, origin throughout the watershed. However, since the start of the Barton Creek monitoring program, the use of this ratio in determining origin has been determined to be less than definitive. Regardless, at Pool 1, the source of fecal coliform is most likely the cattle ranching operations upstream and adjacent to the sampled pool.

- At present, these significant water chemistry differences are rather small and localized. During periods of strong baseflow, enough relatively pristine waters are contributed from Barton Creek's rural and undeveloped areas to dilute impacted discharges from developed tributaries and springs located lower in the watershed. As Barton's watershed develops and more impacted discharges are added, water quality degradation in Barton Creek will likely be more widespread and conspicuous.

- Further development in the Barton Creek Watershed that does not provide adequate baseflow protection and impervious cover limits will most likely be associated with the following impacts during baseflow periods: (1) diminished water clarity in impounded and slower-moving waters, resulting from cumulative impacts of construction-related runoff; (2) replacement of a relatively diverse aquatic flora with a monoculture of *Cladophora* algae below lands where there is potential for mismanagement of effluent irrigation; (3) maintenance of heavier filamentous algae cover in the mainstem owing to nutrient-enriched waters draining to Barton Creek from developed tributaries and springs.

6.3 CANYONS STUDY CONCLUSIONS

- There are significant differences in baseflow nitrate, ammonia, TDS, TSS, and turbidity concentrations between watersheds draining golf course, residential, and rural land uses. Under most analysis groupings, golf course tributaries have higher constituent concentrations than residential tributaries, and both golf course and residential tributaries have substantially higher concentrations for these five parameters than rural tributaries.

- Baseflow data, as indicated by antecedent dry conditions, suggest the nitrate parameter shows the most variation of those measured in the Barton Creek Watershed. A comparison of tributaries characterized by various wastewater treatment strategies reveal that golf course watersheds using sewage effluent irrigation and fully developed residential watersheds on central wastewater systems generate significantly higher nitrate concentrations in their baseflow than residential watersheds irrigating native grass areas with sewage effluent, residential neighborhoods on septic systems, or undeveloped rural watersheds.

- Buffers associated with residential areas using septic systems appear to be functioning to keep excess nutrients and bacteria from reaching surface waters. This finding may also be related to the lower impervious cover associated with larger lot sizes in residential areas on septic systems.

- When water samples are collected simultaneously during storm events from the three selected tributaries representing residential, golf, and rural land use, the representative golf course site is significantly higher in nitrates and ortho-phosphate than the other two land uses, while the representative residential site is significantly higher in pH and lower in TDS than the other two land uses. The residential site's lower TDS illustrates the heavier storm runoff experienced in land uses with more impervious cover.

- Baseflow water quality samples collected contemporaneously from two adjacent residential canyons on central wastewater collection systems indicate that the size of the undeveloped buffer zone around a stream may be related to water quality. Median nitrate concentrations in these two canyons indicate that water quality improves as buffer zone size increases. Furthermore, impacts to pH are reduced in the larger buffer zone watershed.

- In summary, when compared to streams representing rural land use, some form of statistically significant water quality degradation can be documented by Canyon Study results for streams representing golf or residential land use categories.

6.4 SEDIMENT STUDY CONCLUSIONS

- A comparison of lead, copper, and zinc in Barton Creek sediments shows that although they vary from site to site, concentrations generally increase from upstream to downstream .

- PAHs in sediments collected from Barton Springs Pool and the site immediately above the pool were above concentrations shown to have biological effects on aquatic life. Additionally, several organochlorine pesticides were found above TNRCC screening levels at the site immediately upstream of Barton Springs. In contrast, sediments from sites further upstream on Barton Creek showed no significant concentrations of PAHs and pesticides.

- Throughout the Barton Creek Watershed, concentration levels of sediment constituents are not of concern as interpreted using NOAA biological effects levels, with the exception of the area in and around Barton Springs. The increase in concentrations in this area could be attributed to the accumulation of contaminated sediments at this most downstream site, the discharge from the springs of the Edward's Aquifer, or storm runoff from nearby developed areas.

6.5 BIOASSESSMENT STUDY CONCLUSIONS

- Several significant differences were found between the mean concentrations of water quality parameters on Barton Creek and Onion Creek. Total dissolved solids, total suspended solids, nitrate and nitrite, and total phosphorus were all significantly higher in Onion Creek than in Barton Creek. Flow rate and pH were significantly higher in Barton Creek than in Onion Creek.

- Consistent relationships were identified between land use and two important water chemistry parameters - total dissolved solids and nitrate+nitrite-nitrogen.

- After looking at three scales of spatial analysis, it was determined that land use on a watershed scale had the strongest relationship to water quality using multivariate statistical methods and data condensation including principal components analysis. Mitigation of human-caused influences on water chemistry requires the adoption of a whole watershed management approach.

- Both Barton and Onion creeks exhibit low levels of nutrients at upstream sites. The low nutrient levels result in limited productivity and relatively low levels of biological abundance and diversity at upstream sites. As the nutrient levels and flows increase at downstream sites, abundance and richness increase also. This condition is the opposite of the traditional model of ecological integrity, in which unimpacted biological communities exhibit higher levels of abundance and diversity than communities affected by natural and human-caused disturbances.

- Chlorophyll *a* (a measure of algal growth) mean concentrations are different between the land use groups on Barton Creek. Sites with higher levels of residential housing and golf course land use had significantly higher chlorophyll a values than sites with lower levels of each of these land uses.

- The findings of this report suggest that the macroinvertebrate community is responding more dramatically to water quality variation in Onion than in Barton Creek. Creeks with higher mean levels of water column nutrients than Barton may have a more consistent response to chemistry by the macroinvertebrate community. In general, the macroinvertebrate data from the Bioassessment Grant indicate that current levels of biological impairment in Barton Creek are extremely low. Development in the Barton Creek Watershed is still in the early stages, with current impervious cover estimates at about six percent. Onion Creek, however, has impervious cover estimates of 10 percent in the study reach.

- Although all lotic biological communities are subject to temporal variation, it appears from project data that the stream macroinvertebrates have a particularly strong response to both season and flow, which overwhelm other documented variables.

- The relationship of the diatom community to nitrogen with respect to flow and season suggests that diatoms are more closely tied to the water chemistry at the time of sampling than are benthic macroinvertebrates.

- On both Barton and Onion creeks, diatom community changes are related distinctly to watershed changes due to levels of development.

- Extended periods of flow are required for mature biological communities to develop at the study sites. Study results indicate that during extended dry periods, biological communities are unable to survive and such communities are lost as indicators of cumulative effects. As surface flows return to the mainstem of the creeks, the substrate is slowly recolonized by periphyton and benthic macroinvertebrates.

- All relationships between biological communities and environmental parameters other than flow found in this study are conservative estimates because of the extreme flow variations during the project.

- For Barton Creek between Hwy 71 and Lost Creek Blvd., a comprehensive database describing benthic macroinvertebrates and diatom communities has been established.

This information provides a baseline for comparison with biological conditions developing in the future.

6.6 SALAMANDER STUDY CONCLUSIONS

- Surface populations of the Barton Springs salamander have been monitored monthly for 38 months. Total monthly counts, although variable, have not exceeded 45 individuals in the main springs. It should be noted, current methodologies are unable to estimate the size of the subsurface population. Considering the size and physical limitations of this unique habitat, it can be said that the population of salamanders living in Barton, Eliza and Old Mill springs is very much at risk. It is extremely important to continue to monitor any and all ecological fluctuations that may affect this species and its environment. We have seen populations reduced drastically due to natural trauma (storm events) and the slow recovery of that population. We have also seen the salamanders come and go in the secondary springs, depending on quantity of water and availability of habitat. The Barton Springs salamander is responding to obvious environmental changes, but the more subtle chemical and physical changes that affect this organism have yet to be determined.

6.7 SURFACE WATER MODEL CONCLUSIONS

- Deterministic models using the buildup/washoff relationships common to public domain watershed models lack the capability of consistently predicting stormwater quality in the single land use data set developed by the COA Storm Water Monitoring Program (consecutive, multi-event pollutographs). Therefore, these models cannot be used to project water quality in Barton Creek on the basis of land use.

- Despite the extensive database contributed to this study, even more data would be required to sufficiently characterize the consecutive event pollutograph for model calibration purposes.

- For the Barton Creek Watershed above the Recharge Zone, the SWMM model was adequately calibrated to simulate observed creek flows over periods of short duration and partially calibrated to allow general simulations over periods of long duration.

- The observed TSS loads in Barton Creek greatly exceed the loads estimated by the SWMM model because the model does not account for the additional TSS contributed by channel erosion.

- Due to the failure of the deterministic buildup/washoff model, a statistical model was developed with some limited predictive capabilities for simulating stormwater quality in Barton Creek.

- From the data provided by the COA stormwater quality monitoring program, stormwater pollutant loads are more sensitive to changes in stormwater quantity than concentration. Thus, land use changes that increase stormwater quantity (runoff) are especially significant in increasing constituent loads. This finding supports current policy strategy of regulating impervious cover through ordinance restrictions. In addition, this finding indicates the need for impervious cover controls through other jurisdictions outside of the COA portion of the watershed.

- Given the uncertainty in prediction of existing stormwater quality for the Barton Creek Watershed, and the uncertainty on how the predictive parameters which control water quality vary with land use changes, it does not appear that current industry standard public domain stormwater quality models can be used to accurately predict the effects of development on water quality in Barton Creek. For this reason, future efforts using more simplified methods should provide the best focus for Drainage Utility efforts.

6.8 GROUND WATER MODEL CONCLUSIONS

- A parsimonious ground water model was developed which has the ability to predict water movement and water quality in the Edwards Aquifer and at Barton Springs. This model is a tool to evaluate the impacts of urban development on water quality and quantity.

- The data analysis performed for this study did not detect changes in the water quality of Barton Springs over the last 15 years. This attributed to several factors. Impervious cover in the contributing and Recharge Zones accounts for only five to eight percent of the total area and has changed relatively little over the period of study. 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.

- Development simulated in the model changed flow characteristics of recharge creeks, reducing baseflow while increasing the peak flow rates during periods of storm water runoff. Predicted increases in peak flows may also result in more frequent Barton Springs pool closings owing to flooding of the pool by Barton Creek.

- Changes in creek hydrology reduced the overall rate of recharge to the aquifer. Development simulations predict lowering the average discharge of Barton Springs 11 to 34 percent. The increase in impervious cover of the watersheds resulted in more recharge during what would normally have been extended periods of baseflow so that the average *minimum* spring discharge remained unchanged.

- Increased urbanization is likely to reduce the quality of the water recharged to the aquifer. Only the effect of urbanization on nitrogen concentrations was modeled as part of this research. A level of intense development (45 percent impervious cover), was estimated to raise the predicted nitrogen concentration at Barton Springs from about 1.5 mg/L to approximately 3.5 mg/L, an increase of approximately 130 percent. Using a moderate level of development (20 percent impervious cover), the predicted nitrogen concentrations at Barton Springs increased from 1.5 mg/L to 1.8 mg/L, an increase of approximately 20 percent. Average concentrations in the aquifer are predicted to experience similar percentage increases. The greatest impact may be on Barton Springs

Pool and Town Lake, where the increased nutrient supply may promote the growth of algae and euthrophication.

- Septic systems account for only about 10 percent of the nitrogen in the aquifer so an increase in their use should not be a problem unless development reaches a level such that storm water runoff from these sites reduces the quality of the water in the creeks as well.

- 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.

- Changes in recharge quality in Onion Creek will affect water quality in the entire aquifer and 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 increase in impervious cover in the Barton Creek Watershed will result in more recharge events of poor quality water 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.

- Model simulations with varying levels of development indicated that unless urban development on the Recharge Zone dramatically increased the amount of water pumped from the aquifer, there is little danger that Barton Springs would cease to flow under normal rainfall conditions. Recharge from Barton Creek, which accounts for about 30 percent of recharge from all contributing creeks, will continue to discharge at the Springs regardless of changes in water use in other parts of the aquifer.

- During the drought of the 1950's, discharge of the springs was reduced from an average of 50 cfs to less than 10 cfs. Continued population growth and reliance on the aquifer for drinking water may result in even greater reduction in spring flow when a drought of this severity recurs. Low spring flow may pose a serious threat to the Barton Springs Salamander and affect the operation of Barton Springs Pool which draws over 300,000 swimmers annually.

6.9 RETROFIT STUDY CONCLUSIONS

- Development related changes in flow and constituent loads have occurred in the BSZ with the largest changes occurring in the Williamson Creek watershed.

- Urban processes have resulted in higher suspended solids from channel erosion and construction loads in the BSZ.

- Structural retrofits are limited in their effectiveness because of the relatively low percentage of TSS and TN loads which can be captured. However, combining these facilities with flood control structures may provide additional removal by reducing peak flows and capturing construction related TSS.

- Given the magnitude of increase in loadings from predevelopment to developed conditions, retrofits alone cannot cost effectively reduce significantly.

- Site specific BMPs retrofitted into developed areas will also not achieve regionally significant load reductions; however, combined with regional structural BMP's, watershed degradation can be minimized.

- When comparing the relative load reductions from a variety of water quality management strategies, the benefit per cost for rangeland management compared favorably to pond BMPs for TSS and less favorably for TN. Comparisons of other BMPs were complicated by the uncertainties involved in estimating loading reductions.

7.0 PRIORITIES FOR FUTURE MONITORING

This section describes a monitoring program designed to supply water quality information needed for continued management of the Barton Creek Watershed. The purpose of the design process is to prioritize recommendations from previous studies and provide a systematic focused plan for future monitoring in the watershed. The design process consisted of a review of the water quality management methods in current use, the management goal of the City in relation to Barton Creek, and identification of information needed to meet this goal. The information needs were translated into monitoring goals which led to an appropriate evaluation method to be used in the monitoring plan. With this method of design, the future monitoring in the watershed will be based on information gleaned in the field and laboratory during previous studies and provide the scientific and statistical support for management decisions and initiatives.

7.1 CITY OF AUSTIN WATER QUALITY MANAGEMENT

Currently, the City of Austin manages water quality resources in the Barton Creek Watershed through watershed ordinances regulating development, implementation of structural and non-structural Best Management Practices for nonpoint source pollutant control, and cooperation with regional, State, and Federal environmental agencies charged with resource protection. These are the basic tools at the disposal of the City, implemented through the activities of the Drainage Utility Department.

7.2 MANAGEMENT GOAL

The management goal of the City for Barton Creek is the same as that provided by numerous resolutions - to protect the character and water quality of Barton Creek. The Strategies used to meet this goal are regulatory, programmatic, and capital projects necessary to achieve "non-degradation" of water quality in Barton Creek.

7.3 INFORMATION NEEDS

Information needed to support the regulatory, programmatic, and capital strategies of the

City in the Barton Creek Watershed include the following:

- Are current strategies working to protect the character and water quality of Barton Creek?
- Where in the watershed should we concentrate these strategies including location by subwatershed, distance to mainstem or tributary, or by development type or land use?
- What additional strategies may provide more cost-effective protection of the Creek.

These questions do not lend themselves to short term monitoring projects. In order to meet these regulatory information expectations, another more technical question must be addressed first, which is:

- What are the quantifiable impacts of urbanization on the ground water, surface water, sediment, and habitat quality of Barton Creek.

While the studies documented in this report provided insight for the current Drainage Utility policy in Barton Creek, information needs will continue as the watershed is developed. In addition, statistical support for the conclusions provided in previous sections can be improved by altering study design based on the data now available and continuing monitoring where appropriate.

7.4 MONITORING GOALS

In order to plan for continued monitoring in a systematic way, several monitoring goals are used to address information needs and focus on formulating statistical arguments which will support management decision-making. This is done both to ensure that information expectations will be met continually, and the monitoring performed by the City will be economical and of high utility. Achievement of the following monitoring goals is necessary to meet management information expectations:

- Provide early-warning signals of surface and ground water contamination or recovery in Barton Creek Watershed.

- Provide an on-going numerical assessment of watershed patterns or trends in surface water, ground water, sediment, and habitat quality.

- Provide an on-going assessment of the relationships between observed patterns and trends in surface water , ground water, sediment, and habitat quality and development, development restrictions, and implementation of BMPs for nonpoint source pollutant control.

7.5 OBJECTIVES AND STRATEGIES BY PROGRAM AREA

The monitoring goals listed above are implemented through the recommendations provided at the end of individual sections in this report. However; the obvious limitations on staff and budget constrain the Drainage Utility Department to prioritize monitoring within the watershed. Staff used preliminary cost estimates including manhour estimates and a comparative rating considering short and long term benefits of the recommendations to reduce the scope of continued monitoring. The monitoring objectives and strategies that follow are the result of this prioritization process.

7.5.1 Ground water Monitoring Program

Objectives:

- Determine how current levels of urbanization are affecting ground water quality and how continued urbanization affects ground water quality throughout the development process.
- Determine how current practices of land application of effluent are affecting ground water quality.
- Determine if and how water quality of Barton and other springs are changing over time.
- Determine if and how suspended solids are transporting pollutants through the aquifer.
- Determine what are baseline conditions and responses to storm events in contributing watersheds.
- Determine how spring water quality is affected by storm events.

- Determine how water from "bad water line" affects spring water quality during drought and pool maintenance.
- Determine what are the flow paths and migration rates in the aquifer.
- Improve well monitoring effectiveness during low flow conditions.

Strategies:

- Continue to monitor 10 springs at several levels of watershed development annually for conventional pollutant parameters (i.e. nutrients, solids, inorganics).
- Locate and monitor new springs in developing watersheds. It is anticipated that to characterize springs as their watersheds are developed, five springs would be selected and monitored at a frequency of once per year for conventional pollutants.
- Increase monitoring of springs in effluent irrigation areas. Presently, three candidate areas would be suitable for such monitoring at a quarterly frequency for conventional pollutants.
- Continue Barton Springs water quality monitoring at current biweekly frequency for nutrients and TSS and quarterly frequency at five spring sites quarterly for additional conventional pollutants.
- Monitor suspended sediment quality semiannually at Barton Springs.
- Increase heavy metals analysis in Barton and other springs including annual sampling at four springs.
- Continue DataSonde deployment at Barton Springs and increase deployment at three remaining springs for a minimum of two months a year for each spring.
- Continue storm water sampling at Barton Springs and monitor at Old Mill, Eliza, Cold, and Backdoor Springs once annually.
- Monitor water quality of springs during drawdown of pool once annually at four springs for conventional pollutants.
- Continue with tracer studies in BSEA Conservation District by providing in-kind labor match to the district throughout the project.
- Continue recharge event sampling in Barton Creek using information gained from tracer studies.

- Remove sediment from USGS monitoring well YD-58-42-217 (Loop 360) to improve data quality.

7.5.2 Surface Water Monitoring Program

Objectives:

- Determine how continued urbanization is affecting Barton Creek water chemistry and algae growth.
- Determine the frequency and magnitude of transient, potentially cumulative water quality impacts from storm flow at mainstem stations.
- Determine the relationship between the statistical differences in Barton Creek tributary water quality and varying buffer width, impervious cover, or water quality controls.
- Determine how continued urbanization and wastewater disposal affecting tributary water quality.
- Determine how increasing urbanization with regulatory controls affect baseflow water quality in developing tributaries.
- Determine how Barton Creek water quality compares to other Central Texas streams over time.
- Determine if organic contaminants are accumulating in Barton Creek sediment.
- Determine the correlation between dropping concentrations in baseflow during recession to time and flow rate or both and how this can be used to model the response of the system.
- Determine if the definition of spatial differences in water quality in the mainstem of Barton Creek can be improved through increasing sample frequency.
- Determine how continued urbanization is affecting tributary water chemistry.
- Determine if more accurate flow and water quality data in the lower watershed above spring influence can improve calibration of water quantity model.
- Determine if additional rainfall water quality data can provide closure of pollutant balance and better input to model.
- Determine what additional soils and plent data can provide closure of pollutant balance and better input to model.

Strategies:

- Continue quarterly monitoring of eleven mainstem pools for water chemistry and percent algae cover.
- Monitor Pool 3, Barton Creek Blvd. and Lost Creek Blvd., Pool 8, (Or Camp Craft Access) with Datasonde monthly at three sites for continuous field data.
- Compare water quality differences between other watershed attributes such as percent impervious cover, presence of water quality controls, and other ordinance driven characteristics. This requires detailed impervious cover and other watershed information, but no additional monitoring.
- Continue to monitor 38 sites on tributaries to Barton Creek quarterly for conventional parameters.
- Monitor three tributaries to Barton Creek which are currently undeveloped, but planned for development, on a weekly basis for conventional pollutants.
- Coordinate regional Citizens Monitoring in the Austin Area, and calculate annual index of water quality for public information from regional citizen monitoring.
- Monitor sediment quarterly for total petroleum hydrocarbons at four selected mainstem sites and Barton Springs.
- Monitor sediment annually for full suite of toxics parameters including pesticides at four selected mainstem sites and Barton Springs.
- Conduct intensive monitoring of stormflow and baseflow recession following significant event in Barton Creek or others in BSZ. Correlate dropping concentrations in baseflow with time or flow rate or both to understand the basin operation.
- Increase stormwater monitoring at mainstem, USGS-type stations, Hwy 71, and Lost Creek to 3 storms annually.
- Monitor undeveloped but developing streams in the Water Quality Protection Zones (30 TAC 216)(6 storms per year).
- Monitor flow and water quality using station just upstream of Barton Springs Pool possibly at the location of the current USGS discharge measurement station 8155400.
- Increase rainfall water quality monitoring stations and frequency.
- Increase soils and plant monitoring stations and frequency.

7.5.3 Biological Resource Monitoring Program

Objectives:

- Determine how continued urbanization is affecting Barton Creek aquatic biology.
- Determine how the surface salamander population and spring habitat is changing over time.
- Determine if salamander populations and spring habitats are changing over time in Eliza and Old Mill Springs.

Strategies:

- Monitor benthic macroinvertebrates, diatoms, and percent algae cover on a quarterly basis at 3 sites - upstream, midstream, and downstream sites. Obtain chemical and field data concurrently.
- Continue monthly surveys of salamander populations and the general biota of the springs, long-term.
- Survey Eliza and Old Mill Springs monthly.
- Coordinate benthics sampling of percuial pools with TNRCC.

7.6 EVALUATION METHODS AND STATUS

For each of the recommended monitoring programs where it is appropriate, the evaluation methods are chosen to meet monitoring goals. This system is suggested in order to optimize expenditures on water quality monitoring programs (Ward & others, 1990 and Sanders & others, 1983) and details are provided in Appendix G. Specification of the study design criteria in advance of further monitoring was enabled by the data obtained to date for the need to include design for soil/plant/water nitrogebudget analysis. At the end of the next reporting period, it is anticipated that implementation of this design will provide additional support and direction for modifying policies and programs of the City of Austin with respect to water quality management of Barton Creek. In addition to evaluation methods, Appendix G lists the current status of recommended monitoring. The status identifies which are recommended for immediate implementation, implementation within five years, not recommended, underway, or completed. A detailed outline of the recommended monitoring is in preparation and will be implemented in FY97-98.

8.0 POLICY RECOMMENDATIONS

Results from the monitoring carried out in the past seven years suggest the benefit of several fundamental changes in how the City of Austin is managing water quality in the Barton Creek Watershed. These recommendations are compiled from the technical studies documented in this report, as well as from national data, to prompt discussion among citizens and policy makers.

8.1 CONSERVATION EASEMENT PURCHASES

Findings in this report indicate that the water quality of Barton Creek's mainstem, tributaries, and springs remains relatively pristine in rural, relatively undeveloped areas, outside Austin's ETJ. This high quality water from upstream areas seems to mitigate local impacts from areas of relatively dense development in downstream reaches of the creek. It is imperative that the mainstem and tributaries of Barton Creek outside Austin's ETJ also be protected from unregulated development. Therefore, it is recommended that all tributaries qualifying as Waters of the United States according to the Clean Water Act be secured as conservation easements and protected by vegetative buffers or setbacks. These setbacks should increase with closer proximity to Barton Creek. Such purchases can be much more cost-effective than expenditures on engineered retrofits.

It is recommended that, wherever possible, the City's Real Estate Division secure conservation easements around Barton Creek and its tributaries from ranchers and other land owners. Most current land uses outside Austin' ETJ are not impacting water quality; therefore landowners could be paid to maintain and permanently secure these water quality/wildlife corridors from any future development while continuing their ranching activities. Precedents for such a program can be found in the states of Arkansas, Missouri, and Wisconsin. The Wisconsin Department of Natural Resources funds conservation easements around priority watersheds in their state. In order to maximize the protection from these easements, the public should have an opportunity to be involved in these proposed purchases.

Similarly, an interlocal agreement between the State of Texas, the Texas Nature Conservancy, Trusts For Public Lands, the City of Austin, and others may be able to initiate a pilot project similar to that of Wisconsin for purchase of priority watershed easements, in the Barton Creek Watershed. Use of Drainage Utility funds for this purpose may be justified as a more cost effective alternative to water quality pond retrofits, given the benefits noted for buffer maintenance in comparison to that identified in the BSZ retrofit masterplan for retrofit construction. The Federal listing of the salamander will require that all entities with jurisdiction in the watershed comply with the protective efforts required as part of the Endangered Species Act. Therefore, it is recommended that various funding sources be explored for the purchase of easements to the mainstem and tributaries of Barton Creek. A major contribution to this effort could be the development of a multi-agency partnership solely to assist in the acquisition of conservation easements in the watershed.

8.2 LAND ACQUISITION AS A BMP

Data from the pool study presented in this report demonstrate that long reaches of undeveloped watershed can partially mitigate or assimilate water quality degradation that may occur from local impacts upstream. Preliminary investigations by City staff in Walnut Creek also indicate that alternating undeveloped and developed reaches along a creek mainstem can result in significant water quality and habitat recovery through undeveloped drainage areas. Therefore, it is recommended that various funding strategies be explored for the purchase of large tracts of property adjacent to the creek, especially those close to Austin. Acquisitions should be preserved undeveloped or developed at extremely low densities. This approach may be thought of as an in-stream buffer zone at a larger scale than the conservation easements described above. Such a strategy could partially buffer Austin from impacts that may eventually occur in areas of relatively unregulated development in the upper reaches of Barton Creek.

An additional benefit of this strategy would be reduced impervious cover in the watershed. Despite national literature which indicates that stream degradation occurs at relatively low levels of imperviousness (10-20 percent) (Schueler, 1995a), current State protection through the Edwards Aquifer Rules and Water Quality Protection Zones does not provide for impervious cover limits anywhere in the watershed. The current Barton Creek Wilderness Area should operate as a water quality BMP as described above and could serve as a nucleus for additional acquisitions.

8.3 HEADWATER BUFFER ZONE REGULATION

Headwater streams are often degraded or eliminated by urbanization. Findings of this report suggest water quality in such streams may be protected by large native buffer zones around waterways or larger lot sizes. National experts in the field of watershed management recommend protecting the smallest first order streams with a minimum of 100 feet of predevelopment unvegetated buffer (Schueler, 1995b)(Appendix D). First order tributaries are defined as the place where an intermittent stream forms a distinct channel. This is the same definition used to define Waters of the United States according to the Clean Water Act. Austin currently restricts Critical Water Quality Zone protection of its headwater streams by various amounts depending on the size of the entire watershed. It is recommended that Austin's water quality ordinances be improved by protecting all Waters of the United States with a minimum of 100 feet natural buffer zone.

8.4 GOLF COURSE BUFFER ZONE REGULATION

Similar to the above recommendation, a specific buffer zone requirement is indicated for golf course operation. Although proper management of golf course effluent irrigation, turfgrass management, and pest control can reduce any impact from courses to a minimal level, episodic and cumulative impacts were observed in Barton Creek during several of the studies contained in this report. Currently, City of Austin ordinances restrict development in critical water quality zones only in classified watersheds greater than 64 acres. It is recommended that this be revised to require a minimum buffer of 150 ft to any distinct channel draining off-site in a golf course development.

8.5 EFFLUENT IRRIGATION PERMIT REVIEW COORDINATION

Due to changes in TNRCC policies, all wastewater discharge permits in the Colorado River Basin will be reviewed in 1999, including land application disposal permits. Because renewal applications are required to be submitted six months in advance of expiration, review and negotiation of these permits will occur in mid-1998. This gives the City of Austin an unprecedented opportunity to have a consistent coordinated review of all land application permits which have potential to influence Barton Creek water quality. This will also provide the City the opportunity to influence permit provisions on the basis of past operational problems and poor system design. Therefore, it is recommended that City staff formulate guidelines for effluent application that can be incorporated into TNRCC permits through the Permit Application Review Committee currently responsible for protecting the interests of the COA by negotiating special permit conditions. These guidelines may incorporate the results of nutrient budgets and nutrient/pesticide performed by the City of Austin.

8.6 FLOOD CONTROL REGULATION REVISION

City of Austin flood control regulations should be reviewed and potentially revised in light of the importance of Barton Creek channel erosion to pollutant load documented in several studies included in this report. Current regulations, which are based on limiting the peak discharge from a site to predevelopment conditions, may have unintended consequences on flow rates in creeks downstream of discharge points. Depending on the relative position of the site and other factors, some stormwater detention facilities constructed to City standards may increase stormflow rates in the main creek channel downstream of the site compared to developed conditions with no controls in place. The Barton Creek Watershed Model can be used to evaluate the effectiveness of current regulations and predict the impacts of proposed changes to these rules.

8.7 INFILTRATION DEVICE REQUIREMENTS BY REGULATION

Due to the importance of maintaining clean baseflow in promoting health in Barton Creek, infiltration practices are recommended to be promoted through ordinance changes as an effective water quality BMP based on the following conclusions:

- ◊ Analysis of data from single land use watersheds indicate that the amount of effective impervious cover has a greater impact on stormwater loads than land use classification.

◊ Peak flows and sustained high velocities have a dominant impact on water quality due to channel scour and erosion.

◊ The recreational uses of Barton Creek are dependent on the maintenance of a healthy baseflow, which will be enhanced by increasing treated stormwater infiltration through structural and non-structural means.

◊ Promoting baseflow in Barton Creek will help maintain the quality of water recharged to the Barton Springs portion of the Edwards aquifer.

Care in the implementation of this recommendation should be taken to insure that infiltration devices recharge good quality water rather than untreated urban runoff.

8.8 MAINTENANCE OF NATURAL HYDROLOGIC CYCLES

Maintaining natural flow regimes in Barton Creek is critical to the preservation of its unique and valuable character. That is, alterations to predevelopment flow patterns, including velocity, frequency, quantity, and duration of stormflows and baseflows will have impacts to physical, chemical, and biological characteristics of the creek.

Repercussions of flow patterns in the creek are seen clearly in the City's biological studies as the single major influence in biological community development and habitat maintenance. In the ground water, surface water, and modeling projects, flow is correlated with water quality in both long term monitoring and dynamic storm event monitoring. In the retrofit masterplan and modeling projects, control of erosion resulting from increases in peak flows is identified as a priority for water quality protection and maintenance of recreational facilities. Several other recommendations such as that for infiltration devices, review of flood control recommendations, and watershed scale planning are related to the importance of maintaining the natural hydrologic cycle. The preponderance of the City's investigations identify natural flow patterns as an influence in baseline results. In a recent compilation of studies the importance of maintaining natural hydrologic cycles was emphasized for protection of water quality and biota (Herricks, 1995).

Therefore, it is recommended that in implementing the mission of the Drainage Utility for protection of water quality, erosion control, and flood protection in the Barton Creek Watershed, management strongly consider the repercussions of altering the natural flow patterns and hydrological cycle. Furthermore, it is recommended that the Drainage Utility undertake review of ordinance and programs to enhance protection of the underlying hydrological environment of Barton Creek which influences much of its unique value to the citizens of Austin. This review would include any ordinances or variance procedures which influence impervious cover, infiltration devices, constructed or protected wetlands, tributary rerouting, or drainage area modifications.

8.9 WATERSHED SCALE PROTECTION

Through studies conducted nationwide since the 1972 Clean Water Act, consensus has developed in technical and regulatory communities that a watershed-based approach to nonpoint source pollution control is necessary for the success of water quality protection efforts (Water Environment Federation, 1996). This strategy is especially important in the Barton Creek Watershed because of the many jurisdictional boundaries that overlap within the watershed boundaries. Currently, only 41 percent of the watershed is under the jurisdiction of any City of Austin watershed ordinance. Hundreds of acres of the area inside of the City's ETJ were permitted, under Senate Bill 1704 (now defunct), to use ordinance standards which are less protective that those deemed necessary and provided for in the City's current ordinance (the SOS ordinance). Furthermore, an unknown percentage of the watershed under the City's jurisdiction could potentially be exempted from compliance with City ordinances through establishment of special "Water Quality Protection Zones", entities created by State legislation (Senate Bill 1017, 30 TAC 216) during the last legislative session. Rules developed for the Zones are also not as stringent as those deemed necessary by City staff to protect the creek and the aquifer. To date approximately 2,000 acres in the Barton Creek Watershed have been exempted through this process. Of course, many more acres in other watersheds which contribute recharge to the Edwards Aquifer are also eligible for exemption from City ordinances through the above-described legislation.

It is the opinion of City staff that current State regulations for the protection of the Edwards Aquifer (30 TAC 213) will not fully provide for non-degradation of the aquifer. Protection of the Contributing Zone, where approximately 85 percent of aquifer recharge originates, is particularly inadequate.

For these reasons, it is imperative that the City redouble efforts to forge partnerships at State, County, and local, and potentially Federal levels with the goal of a more unified and effective watershed-based plan for the protection of Barton Creek and the Edwards Aquifer.

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Appendix A – Physical Description and Settings of Barton Creek Study Pools

APPENDICES

APPENDIX A PHYSICAL DESCRIPTION AND SETTINGS OF BARTON CREEK STUDY POOLS

Pools for the Barton Creek Watershed Study were selected by ECSD staff during 1990 following extended dry weather and very low flow conditions on the creek. In fact, surface flow was commonly nonexistent; pools were fed by creek underflow moving through channel alluvium or small local springs. Selecting pool monitoring sites under these flow conditions assured that these sites would retain water under even very dry conditions. The drawback was that while water depths were shallow during low flow, they often were over five feet under normal conditions, making winter surveys difficult. Springs discharging from a discrete point are evident in or upstream of five of the nine study pools.

These pools were remarkably stable during the study. The overall shape of the pools was constant, though pool depths commonly change in response to flow conditions. Gravel bars commonly migrate and change sizes within pools, but these bars apparently have had little effect on the pools. Only one pool, Pool 2, changed as a result of high stormflows, which reshaped gravel bars forming pool boundaries. This consistency suggests that once formed, pools are present for a relatively long period of time, transformed perhaps only during exceptionally large floods.

All pools in the watershed study are underlain by the Glen Rose Formation. This formation is characterized by interbedded limestone, dolomitic limestone, and marls (calcareous or limy clays) (Barnes, 1974, 1981). Quaternary alluvial sediments are significant components of specific pool site characteristics and channel morphology. These sediments consist of paleochannel and flood plain deposits of ancestral Barton Creek composed of boulder to gravel-size limestone and finer-grained mixed limestone and clays. They range from moderately to well cemented. Successive levels of flood plain terraces are locally prominent. Natural creek channel downcutting has left these sediments above frequently flooded horizons.

General creek morphology consists of a usually asymmetrical flood plain valley of gently curving to moderately meandering channel with associated cutbanks and point bars. Cutbanks form on the outside curve and are the most active sites of erosion and typically have steeper slopes. Entrenched meanders can form spectacular limestone cliffs. Point bars are located on the inside of channel curves and meanders and are generally sites of sediment deposition. Point bars are commonly covered with gravel adjacent to the creek channel and with finer sediment further away from the creek. Shallow flood channels cutting across point bars are common, formed by high energy water straightening out channel curves during floods.

Pool 1

Pool 1 is the uppermost pool in the watershed study, located approximately 44 miles upstream of the creek mouth. Upstream drainage is approximately six square miles. The pool is located in a relatively straight reach of the creek. Site characteristics include broad flood plains with riparian woodlands, low relief, and gentle slopes to the creek channel. The valley is broad with gently rolling hills in this area. Flood plains and channel banks consist of mixed cobble, gravel, sand, silt and clay Quaternary and recent alluvial sediments approximately six to 10 feet thick. No bedrock outcrops are present in the immediate pool area, although the pool has a bedrock bottom. Surrounding land use is rural with grazing immediately upstream of the site.

A man-made dam four feet high forms the upper end of the pool. Water flows over the dam under all but the most severe drought conditions. An alluvial gravel bar partly dams the downstream end of the pool.

Dimensions of the Pool 1 have not change since ECSD staff began investigations at the site in 1990 . The pool bottom is typically bedrock covered with a veneer of sediment and algae. Channel banks are approximately three feet high and well vegetated. Several sycamore trees provide a high canopy over the pool.

Pool 2

Pool 2 is located immediately downstream of the Fitzhugh Road low-water crossing over Barton Creek. The pool is 34 miles upstream of the mouth and has approximately 42 square miles of watershed upstream of the site. The pool is located on the upstream side of a large meander bend. Site characteristics include broad flood plains with mixed pasture and riparian woodlands, a large alluvial gravel bar on the south side with thick understory vegetation and short drops to the creek floor, and Quaternary terrace bank on the north side with 8-10 foot drops to the creek. This terrace bank is currently undergoing severe erosion during flood events, as evidenced by steep unvegetated slopes, exposed roots, and undercut trees. Bedrock exposures are limited to the channel floor and short vertical faces along the cutbank of the channel. Land use is predominantly rural in the area of the pool.

An alluvial gravel bar partly dams the lower end of the pool. The upper end is currently defined by the upstream-most extent of pooled water. Large flood flows during 1991 dramatically altered the size of this pool by removing part of the downstream gravel dam and scouring out channel sediment forming the upstream end of the pool. Fitzhugh Road crosses approximately 100 feet upstream of the site, and a large impoundment is located 300 feet upstream of the pool. Maidenhair fern is present along the bottom of the terrace bank just upstream of the pool and small amounts of water can be seen flowing into the channel. A small spring (<1 gpm) discharges to the middle of the pool.

The Pool 2 has been reduced in size since the 1991 floods and is now much shorter. Bedrock, with a veneer of sediment, and local gravel bars form the pool bottom. Banks are approximately four to six feet on the alluvial bar side and eight to 10 feet on the terrace side. Large trees provide a fairly dense high canopy.

Pool 3

Pool 3 is located in a creek reach with numerous entrenched meanders. The site is 27 miles upstream of the mouth and has a drainage area of 65 square miles. The pool is located equidistant between meanders. Several terrace levels are evident approaching the creek, formed as the channel downcuts and migrates toward the cutbanks, leaving a broad, open flood plain between meanders and very asymmetrical flood plain profiles in meanders with steep, high cliffs on cutbank sides and large gently rolling flood plains on the point bar side. At the pool site, bedrock exposures are evident in the channel immediately upstream of the pool but not generally along the pool banks. Site characteristics include a huge gravel bar on the east side of the pool, which completely blocks channel flow under low-flow conditions, and an older terrace bank on the west side. Riparian vegetation is partly cleared for grazing on the west side, and numerous small sycamores grow on the alluvial gravel bar. Banks are fairly steep on both sides of the pool, extending six to 10 feet above the channel. Land use is rural with low intensity grazing adjacent to the pool.

The pool is formed by a gravel dam on the downstream end of the pool. The upper end is a bedrock drop-off. Thick gravel, sand, and silt cover the pool bottom. Poorly vegetated, loose alluvial gravel forms the east bank, and grassy, shrub-covered soil forms the west bank. These banks vary from six to 10 feet high, measured from the channel bottom. Floods periodically shift in-pool gravel bars and add or remove sediment, but the pool shape has been constant since 1990. Small bank shrubs locally shade the pool, which is otherwise exposed to full sun.

The creek approaches the pool across a reach of numerous gravel bars and pools. About 150 feet upstream of the pool, a huge gravel bar extending several hundred feet along the east side of the channel partly blocks the channel, forcing flow along the west bank. The creek flows across a short bedrock reach as it enters the pool. The creek winds through several smaller gravel bars downstream of the pool.

Pool 4

Pool 4 also occurs in a creek reach with numerous large meanders. It is 25 miles upstream of the mouth and has an upstream drainage area of 75 square miles. The site is very similar to Pool 3, but it has not been grazed in many years. The pool is about two hundred feet upstream of a meander. The creek flood plain is broad between the meanders with low-relief approaches on the point bar side and steep drop-offs on the cutbank side. Vegetation is generally well-established on both banks. Poor bedrock exposures are present on the west bank just above normal water level. The east side of the pool is formed by an extensive alluvial gravel bar six to eight feet thick forming the flank of a point bar system. The west bank is formed by a terrace deposit about 15 feet thick overlaying bedrock. The terrace contact is about eight feet above the channel bottom (three to four feet above normal water levels). Base of the terrace is well cemented, similar to that seen at Pool 6. The base of the terrace bank and the underlying Glen Rose are covered with maidenhair ferns and moss. Measurable water discharges along the contact from several locations following wet periods. Land use is generally rural.

Barton Creek passes through a riffle-pool reach dominated by alluvial gravel bars, passing a low water crossing about 100 feet upstream of the pool. During low flow conditions, the creek generally does not flow over the crossing but passes through gravel collecting on the upstream side of the crossing and discharges into small culverts under the crossing. The creek passes over, or through during low flow, a gravel bar forming the downstream end of the pool.

Pool 4 has maintained its dimensions during the study despite several floods and the local abundance of readily transportable gravel. The pool has gravel bars at each end which gradually slope into the pool. A bar in the middle of the pool has changed shape several times as a result of flooding. Creek banks are six to eight feet high and steep at the bottom and four to 15 feet high and locally very steep on the west side. Two large trees shade parts of the pool but generally the canopy is open.

Pool 5

Approximately 75% of the watershed, or 90 square miles of drainage area, is present upstream of the Pool 5. The pool is 21 miles upstream of the creek mouth, immediately upstream of the Highway 71 bridge, and a few hundred feet downstream of the confluence with Little Barton Creek. Flood plains in Barton Creek become narrower in this area, as the creek is flanked by higher valley walls. Site characteristics include a steep vegetated bank on the west side and a poorly vegetated large, six-foot thick alluvial gravel bar on the east side with pasture land further east on the flood plain. Land use is rural with some locally heavy development in the community of Bee Cave on Little Barton Creek.

The pool is formed by a natural gravel bar on the downstream end which pools water to a gravel bars on the upstream end. Barton Creek traverses numerous gravel bar upstream of the site; whereas, Little Barton is commonly flowing over bedrock exposures. A large gravel bar partly blocks flows and diverts Barton Creek to the west bank immediately upstream of Little Barton.

The pool bottom is locally bedrock with gravel and sediment on the east sides and upper and lower ends. Channel banks are one to three feet high measured from the channel floor. The gravel bar on the east side is poorly vegetated with scattered small sycamores and extends several hundred feet along the east bank of the creek. The west bank rises from the channel and slopes up steeply some 30 to 40 feet. The pool is well shaded by surrounding trees.

Pool 6

Pool 6 is located approximately 14 miles upstream of the mouth and has a drainage area of approximately 98 square miles. The pool is in an area of entrenched meanders which have eroded spectacular cliffs overlooking the creek and is midway between creek bends. The flood plain is narrow, confined on the east side by high bluffs and on the west by 15 to 20 foot ledges cut into well-indurated terrace deposits. Site characteristics include well vegetated riparian woodlands on the east side and mixed woodlands, pasture, and maintained landscaping on the west side. Land use in the immediate area includes low density residential homes on septic systems and small grazed pastures. Bedrock exposures are limited in the creek proper, but numerous excellent outcrop profiles of ancestral channel sediments about 15 feet thick are present on the west side. These deposits consist of interbedded upward-coarsening sequences of gravel and fine sand.

An extensive alluvial gravel bar blocks the main channel immediately upstream of the pool, forcing the creek through a set of 90 degree turns leading into the study pool. The gravel bar forms the east bank of the pool and runs for several hundred feet downstream. The creek flows across a series of gravel bars and scour pools downstream of the site.

The study pool has remarkably maintained original shape despite the abundance of loose material adjacent to and upstream of the pool. The pool bottom is gravel and fine sediment that has shifted numerous times over the course of the study period. The east bank is poorly consolidated alluvial gravel with scattered small sycamore trees and small shrubs. This bank is steep and about eight feet high. The west bank is formed by a mixture of fallen blocks of terrace gravel, limestone blocks, and vegetated fine sediment which rises gradually from the creek. This bank forms at the base of a cut bank 15 to 20 feet tall of cemented terrace deposits. Maidenhair ferns and mosses mark the location of local ground water seepage at the contact of the terrace and underlying Glen Rose limestone about six feet above the channel. The pool is exposed to the sun with shade coming in the late afternoon by vegetation on top of the west bank.

Pool 7

Pool 7 is 11 miles upstream of the creek mouth and has an upstream drainage area of 101 square miles. Terrace deposits cover the broad flood plain before giving way to steep valley walls of the Glen Rose Formation. Deposits are approximately six to eight feet thick adjacent to the study pool with well developed bedding and soil profiles. Locally, the flood plain has been cleared or thinned for grazing. Bedrock exposures are common along the creek bank about three to four feet above the water. Relief is gentle in the flood plain to the creek. The pool is located 2000 feet upstream of a sharp meander.

A four foot high dam about 20 feet upstream of the study pool backs up water for about 200 feet upstream. Water in the pool is several feet deep under normal conditions. A low-water crossing forms the upper boundary of the pool. Downstream of the pool, water passes over a series of gravel bars and scour pools before reaching a second low man-made dam.

Pool 7 is one of the largest and shallowest of the study pools. Water depths are typically one foot or less. Bottom substrate consists of bedrock and thin layers of gravel and very fine sediment. Channel banks are two to three feet and steepen sharply on the south side of the creek where erosion is cutting into terrace sediments. Vegetation is well established, even with grazing, where erosion is not removing soil. The pool is open to sunlight, and there is only scattered shade in the lower end of the pool.

Pool 8

Pool 8 is in the most heavily developed reach of the creek. It is nine miles upstream of the mouth and has a drainage area of 108 square miles. The pool is located at a sharp bend in the channel, which produces a steep cliff face on the south side and a broad gentle terrace and alluvial flood plain on the north side. The terrace flood plain is well vegetated and maintained as residential lawns. The alluvial flood plain has scattered shrubs and bunch grasses. Bedrock outcrops make up the entire south side of the channel.

Barton Creek is partly dammed behind a low-water crossing about 500 feet upstream of the pool. The creek passes under a bridge and flows across a gravel bar and bedrock reach of channel before entering the pool. Downstream of the study pool, the creek flows through a series of deep pools and low man-made dams. A significant terrace spring discharges into the creek in the bedrock reach upstream of the pool. Terrace deposits are 25 feet thick in this area.

An alluvial dam forms the lower end of the pool, and at the upper end is a small gravel bar below a bedrock reach of the creek. Pool depths vary, reaching four feet in the channel center and only a few inches along the banks. Bedrock covers most of the pool bottom, along with sediment. Channel banks are four to six feet high and steep on the south side with the cutbank before meeting the cliff face. The point bar on the north side allows gentle banks one to two feet high. The pool is well shaded by trees on the north side and the cliff on the south side.

Pool 9

Pool 9 is the most downstream pool in the study. It is 6 miles upstream of the mouth and has a drainage area of 109 square miles. The creek is in a deep canyon at this point, with a narrow flood plain 30 to 50 feet wide on each side. Cliffs reach 100 feet high on either side of the creek. The flood plain is part of the Barton Creek greenbelt park system and so remains a diverse riparian woodland. The pool is in a straight reach of channel. Bedrock exposures are limited to the cliff walls; whereas, alluvium occupies the channel banks.

Barton Creek leaves a series of deep pools formed by several low man-made dams upstream of the study pool. Under low flow conditions, water typically does not flow over the low dams but returns to the creek via underflow through alluvial sediments. The creek enters the Recharge Zone of the Barton Springs segment of the Edwards Aquifer at the downstream end of the pool. Under low flow conditions, water does not usually flow for more than 100 feet downstream before entering the aquifer.

Pool 9 is one of the deepest in the study. Water depths are commonly four to five feet . Very little infilling has occurred in this pool, possibly because the narrow flood plain concentrates high flows and regularly scours loose sediment from the pool. A mixture of fine and coarse sediment covers the pool floor. Channel banks are four to five feet high, but only one to three feet high above water level, and are well vegetated. Large trees provide abundant shade; although, the middle of the pool is open to sunlight.

Appendix C – Parameters and Methods List

Appendix C

Parameters with Analysis Method

Parameter	Methods of Analysis				Parameters Analyzed: Surface Water	Parameters Analyzed: Ground-water	Parameters Analyzed: Sediment
LCRA, NET, COA Water & Wastewater Laboratories							
Anions							
Chloride	SM 4500-Cl	EPA 300	EPA 9252	EPA 9252		X	
Fluoride	SM 4500-F	EPA 340.2	.	.		X	
Sulfate	SM 4500-S0$_4$	EPA 375.4	EPA 9038	EPA 300		X	
Metals							
Antimony	SM 3500-Sb	EPA 200.7	EPA 6010	.		X	X
Arsenic	SM 3500-Ar	EPA 206.2	EPA 6010	.		X	X
Barium	SM 3500-Ba	EPA 200.7	EPA 6010	.		X	
Beryllium	SM 3500-Be	EPA 200.7	EPA 6010	.		X	
Cadmium	SM 3500-Sb	EPA 213.2	EPA 6010	.		X	X
Calcium	SM 3500-Ca	EPA 200.7	EPA 6010	.		X	
Chromium	SM 3500-Cr	EPA 218.2	EPA 6010	.		X	X
Copper	SM 3500-Cu	EPA 220.2	EPA 6010	.		X	X
Iron	SM 3500-Fe	EPA 200.7	EPA 6010	.		X	
Lead	SM 3500-Pb	EPA 239.2	EPA 6010	.		X	X
Magnesium	SM 3500-Mg	EPA 200.7	EPA 6010	.		X	
Manganese	SM 3500-Mn	EPA 200.7	EPA 6010	.		X	
Mercury	SM 3500-Hg	EPA 245.1	.	.		X	X
Molybdenum	SM 3500-Mo	EPA 200.7	EPA 6010	.		X	
Nickel	SM 3500-Ni	EPA 200.7	EPA 6010	.		X	
Potassium	SM 3500-K	EPA 258.1	EPA 6010	.		X	
Selemium	SM 3500-Se	EPA 270.2	EPA 6010	.		X	X
Silver	SM 3500-Ag	EPA 272.2	EPA 6010	.		X	X
Sodium	.	EPA 200.7	EPA 6010	.		X	
Strontium	SM 3500-Sr	.	EPA 6010	.		X	
Thallium	SM 3500-Ti	EPA 279.2	EPA 6010	.		X	
Zinc	SM 3500-Zn	EPA 200.7	EPA 6010	.		X	X

SM - Standard Methods for the Exmination of Water and Wastwater

EPA - Environmental Protection Agency Methods for Chemical Analysis of Water and Wastes

Appendix C
Parameters with Analysis Method

Parameter	Methods of Analysis				Parameters Analyzed		
					Surface Water	Ground-water	Sediment
Acid Volilate Sulfides	n/a	n/a	n/a	.			X
Alkalinity	SM 2320 B	EPA 310.1	.	.		X	X
Alkalinity, Bicarbonate	SM 2320 B	EPA 310.1	.	.		X	X
Alkalinity, Carbonate	SM 2320 B	EPA 310.1	.	.		X	X
BETX plus Chlorobenzees	.	EPA 602/1	EPA 624	EPA 8141		X	X
Biochemical Oxygen Demand	SM 5210 B	SM 2320 B	.	.		X	X
Carbon, Total Organic	SM 5310 B	EPA 415.2	.	.	X	X	X
Chemical Oxygen Demand	SM 5220 D	EPA 410.4	EPA 410.2	.	X	X	X
Chlorinated Herbicides	.	EPA 615	.	EPA 8150A		X	X
Fecal Coliform	SM 9222 D	SM 9221 E	.	n/a	X	X	X
Fecal Streptococci	SM 9230 C	.	.	n/a		X	X
Grain Size/Texture	.	.	.	EPA 600/2			X
Hardness	SM 2340	EPA 130.2	.	n/a		X	X
MBAS (Surfactants)	SM 5540 C	EPA 425.1	.	n/a		X	X
Nitrogen, Ammonia	SM 4500-NH3 F	EPA 350.3	.	EPA 350.1	X	X	X
Nitrogen, Nitrate	.	EPA 352.1	.	EPA 300	X	X	X
Nitrogen, Nitrate/Nitrite	.	EPA 353.4	EPA 353	EPA 353.2	X	X	X
Nitrogen, Total Kjeldahl	.	EPA 351.4	EPA 351.3	EPA 350.2	X	X	X
Oil & Grease	.	EPA 413.1	EPA 413.2	EPA 413.1		X	X
Organics, Semi-volatiles (BNAs)	.	EPA 625	.	EPA 8270		X	X
Organics, Volatile	.	EPA 625	.	EPA 8240		X	X
Organophosphorous Pesticides	.	EPA 622	.	EPA 8141		X	X
PAHs	.	EPA 625	.	EPA 8270		X	X

SM - Standard Methods for the Exmination of Water and Wastwater
EPA - Environmental Protection Agency Methods for Chemical Analysis of Water and Wastes

Appendix C
Parameters with Analysis Method

Parameter	Methods of Analysis				Parameters Analyzed: Surface Water	Parameters Analyzed: Ground-water	Parameters Analyzed: Sediment
PCBs per Aroclor	.	EPA 608	.	EPA 8081		X	X
PCP	.	EPA 625	.	EPA 8270		X	X
Pesticides & PCBs	.	EPA 608	.	EPA 8080		X	X
Phenols, Total	.	EPA 420.1	.	EPA 9065		X	X
Phosphorus, Othrophosphorus	SM 4500-P C	EPA 365.2	EPA 300.0	EPA 365.1	X	X	X
Phosphorus, Total	SM 4500-P E	EPA 365.2	EPA 365.3	EPA 365.4	X	X	X
Total Suspended Solids	SM 2540 D	EPA 160.2	.	n/a	X	X	X
TPH	.	EPA 418.1	.	EPA 418.1		X	X
TPH-Diesel & Motor Oil	.	.	EPA 8015 M	.		X	X
Volatile Suspended Solids	SM 2540 E	EPA 160.3	.	EPA 8060	X		X
Coastal Science Laboratories, Inc							
Nitrogen, Isotope $^{15}N/^{14}N$	Isotopic Fractionation & Mass Spectro.				X	X	

SM - Standard Methods for the Exmination of Water and Wastewater
EPA - Environmental Protection Agency Methods for Chemical Analysis of Water and Wastes

Appendix C
Parameters with Analysis Method

Parameter		Methods of Analysis	Parameters Analyzed: Surface Water	Parameters Analyzed: Ground-water	Parameters Analyzed: Sediment
City of Austin - Environmental Resouces Management Lab					
Lab Equipment					
Fecal Coliform	SM 9221 E	Membrane Filter	X	X	
Nitrogen, Ammonia	n/a	*Colormetric-Salicylate - HACH 8155	X	X	
Nitrogen, Nitrate	n/a	*Colormetric-Cadmiun Reduction - HACH 8171	X	X	
Phosphorus, Orthophosphorus	SM 4500 P E	*Colormetric-Phospho-Moybdate Method-8048	X		
Solids, Total Suspended	SM 2540 D	Gravimetric	X		
		** Analysis on a HACH DR2000 Spectrophotometer*			
Field Equipment					
pH	EPA 150.1	Corning M90 - pH Electrode	X		
	EPA 150.1	Hydrolab - pH Electrode	X	X	
	EPA 150.1	Horiba - pH Electrode		X	
Specific Conductance/	EPA 120.1	Corning M90-Conductivity Electrode	X		
Total Dissolved Solids	EPA 120.1	Hydrolab	X	X	
	EPA 120.1	Horiba - Electrode		X	
Temperature	EPA 170.1	Hydrolab - Thermistor	X	X	
	EPA 170.1	Horiba - Thermistor		X	
Dissolved Oxygen	EPA 360.1	Corning M90- Polargraphic Cell			
	EPA 360.1	Hydrolab - Polarographic w/ 1mil Teflon	X	X	
	EPA 360.1	Horiba-Membrane Galvanic Cell		X	
Oxidation-Reduction Potential	SM 2580	Hydrolab - Pt Electrode	X		
Turbidity	EPA 180.1	Hydrolab - ISO 7027 Nephelometric	X	X	
	EPA 180.1	Horiba - Scattered/Transmitted Light-Nephelo.		X	
	n/a	HACH 8237- Absorptometric Method-Formazin	X		
	EPA 180.1	HACH 16800 - Nephelometric Turbidimeter	X		
Depth (Level)	n/a	Hydrolab - Strain-guage Transducer		X	
Flow	n/a	Marsh McBirney - Electromagnetic	X	X	

• - *Information Not Available*

Appendix D – Benefits of Urban Stream Buffers

APPENDIX D BENEFITS OF URBAN STREAM BUFFERS

The following 20 benefits of urban stream buffers is extracted from Schueler, T., 1995, The Architecture of Urban Stream Buffers: Watershed Protection Techniques, Vol. 1, Number 4, p. 155-165. An (f) means that the benefit is amplified or requires forest cover.

1. **Reduces watershed imperviousness by five percent.** An average buffer width of 100 feet protects up to five percent of watershed area from future development.

2. **Distances areas of impervious cover from the stream.** More room is made available for placement of BMPs, and septic system performance is improved. (f)

3. **Reduces small drainage problems and complaints.** When properties are located too close to a stream, residents are likely to experience and complain about backyard flooding, standing water, and bank erosion. A buffer greatly reduces complaints.

4. **Stream "right of way" allows for lateral movement.** Most stream channels shift or widen over time; a buffer protects both the stream and nearby properties.

5. **Effective flood control.** Other, expensive controls not necessary if buffer includes the 100-year floodplain.

6. **Protection from streambank erosion.** Tree roots consolidate the soils of floodplain and stream banks, reducing the potential for severe bank erosion. (f)

7. **Increases property values.** Homebuyers perceive buffers as attractive amenities to the community. Ninety percent of buffer administrators feel buffers have a neutral or positive impact on property values. (f)

8. **Increased pollutant removal.** Buffers can provide effective pollutant removal for development located within 150 feet of the buffer boundary, when designed properly.

APPENDIX D (cont.)

9. **Foundation for present or future greenways.** Linear nature of the buffer provides for connected open space, allowing pedestrians and bikes to move more efficiently through a community. (f)

10. **Provides food for habitat for wildlife.** Leaf litter is the base food source for many stream ecosystems; forests also provide woody debris that creates cover and habitat structure for aquatic insects and fish. (f)

11. **Mitigates stream warming.** Shading by the forest canopy prevents further stream warming in urban watersheds. (f)

12. **Protection of associated wetlands.** A wide stream buffer can include riverine and palustrine wetlands that are frequently found along the stream corridor.

13. **Prevents disturbance to steep slopes.** Removing construction activity from these sensitive areas is the best way to prevent severe rates of soil erosion. (f)

14. **Preserves important terrestrial habitat.** Riparian corridors are important transition zones, rich in species. A mile of stream buffer can provide 25-40 acres of habitat area. (f)

15. **Corridors for conservation.** Unbroken stream buffers provide "highways" for migration of plant and animal populations. (f)

16. **Essential habitat for amphibians.** Amphibians require both aquatic and terrestrial habitats and are dependent on riparian environments to complete their life cycle. (f)

17. **Fewer barriers to fish migration.** Chances for migrating fish are improved when stream crossings are prevented or carefully planned.

18. **Discourages excessive storm drain enclosures/channel hardening.** Can protect headwater streams from extensive modification.

19. **Provides space for stormwater ponds.** When properly placed, structural BMPs within the buffer can be an ideal location for BMPs that remove pollutants and control flows from urban areas.

20. **Allowance for future restoration.** Even a modest buffer provides space and access for future stream restoration, bank stabilization, or reforestation.

Appendix E – Regulatory Water Standards

APPENDIX E

Regulatory Water Standards

Standards of Chemical Quality have been established by Title 30, Sections 290.103 and 290.113 of the Texas Administrative Code and are regulated by the Texas Natural Resources Conservation Commission (TNRCC). Primary standards, promulgated in Section 290.103, establish the maximum concentration level (MCL) allowable in drinking water for inorganic chemicals, fluoride, and organic compounds. Secondary standards, set forth in 30 TAC 290.113, establish maximum concentrations for additional chemicals not included in the primary standards. Federal amendments to the Safe Drinking Water Act are included below.

Federal Safe Drinking Water Act Amendments 1996

Contaminant	MCL (mg/L)
Antimony	0.006
Arsenic	0.05 (interim)
Asbestos (fiber length > 10 um)	7 MFL
Barium	2
Beryllium	0.004
Cadmium	0.005
Chromium (total)	0.1
Copper	Action Limit = 1.3
Cyanide	0.2
Fluoride	4
Gross Alpha Emitters	15 pCl/L

APPENDIX E (cont'd)

Contaminant	MCL (mg/L)
Gross beta particle and Photon Emitters	4 mRem
Lead	Action Limit = 0.015
Mercury (inorganic)	0.002
Nickel	0.1
Nitrate-N	10
Nitrite-N	1
Radium 226 plus 228	5 pCl/L
Selenium	0.05
Thallium	0.002
Organic Chemicals (56)	0.00000003 - 10 (varies with chemical)
Microbiological	<1 (#/100/mL)

State MCLs for Primary Standards of Chemical Quality

Chemical	MCL (mg/l)
Antimony	0.006
Arsenic	0.05
Barium	2.0
Beryllium	0.004
Cadmium	0.005
Chromium	0.1
Fluoride	4.0
Mercury	0.002
Nickel	0.1
Nitrate & Nitrite (Total)	10.0
Selenium	0.05
Thallium	0.002

APPENDIX E (cont'd)

State MCLs for Secondary Standards Constituents

Contaminant	Level (mg/l)
Aluminum	0.05 to 0.2
Chloride	300
Copper	1.0
Fluoride	2.0
Iron	0.3
Manganese	0.05
pH	≥ 7.0
Silver	0.10
Sulfate	300
Total Dissolved Solids	1,000
Zinc	5.0

State surface water quality standards and screening levels are set by the TNRCC. The following information for Barton Creek is from The State of Texas Water Quality Inventory, 13 Edition of June 1996, Volume 3.

Surface Water Standards and Screening Levels for Segment 1430
Barton Creek

Standards Criteria	
Temperature (C)	32.22
Dissolved Oxygen (mg/L)	5
PH	6.5 - 9
Chloride (mg/L)	40
Sulfate (mg/L)	40

APPENDIX E (cont'd)

Standards Criteria	
Total Dissolved Solids (mg/L)	500
Fecal Coliform (#/100ml)	400
Screening Levels	
Ammonia (mg/L)	1
Nitrite+Nitrate (mg/L)	1
Orthophosphorus (mg/L)	0.1
Total Phosphorus (mg/L)	0.2
Chlorophyll (ug/L)	30

Appendix F – Barton Creek Report Site Number List

Appendix F
Barton Creek Report Site Numbers

Study	BC Report #	Site Name	Latitude	Longitude
Bioassessment	50	BC#3	30.297	-97.852
Bioassessment	53	BC#4	30.294	-97.851
Bioassessment	59	BC#6	30.291	-97.843
Bioassessment	61	BC#7	30.286	-97.849
Bioassessment	66	BC#8	30.282	-97.852
Bioassessment & Sediment	23	BC#0	30.295	-97.927
Bioassessment & Sediment	34	BC#1	30.289	-97.899
Bioassessment & Sediment	75	BC#10	30.274	-97.842
Canyon	2	STT	30.244	-98.124
Canyon	9	FIT	30.245	-98.075
Canyon	11	ROC	30.267	-98.021
Canyon	16	WHC	30.264	-97.969
Canyon	18	LPT	30.276	-97.945
Canyon	19	GMC	30.276	-97.945
Canyon	25	BCT	30.300	-97.919
Canyon	26	SHD#2	30.302	-97.901
Canyon	27	SHD#1	30.303	-97.902
Canyon	28	BCW#1	30.299	-97.898
Canyon	29	UPT3	30.296	-97.898
Canyon	30	UPT2	30.292	-97.902
Canyon	31	UPT1	30.290	-97.901
Canyon	33	UPTS	30.279	-97.901
Canyon	40	EBC	30.287	-97.881
Canyon	41	BCW	30.296	-97.881
Canyon	45	Pool #6 Trib #2 (OGT2)	30.307	-97.868
Canyon	46	Pool #6 Trib #1 (OGT1)	30.305	-97.869
Canyon	47	POD 9	30.300	-97.865
Canyon	48	CCT	30.302	-97.858
Canyon	49	BCW1a	30.306	-97.890
Canyon	54	LJST	30.292	-97.851
Canyon	58	CAM	30.293	-97.843
Canyon	60	CRT#2	30.287	-97.849
Canyon	65	LCC	30.283	-97.852
Canyon	69	SSB1	30.272	-97.855
Canyon	71	SSB	30.276	-97.846
Canyon	77	LCPT	30.275	-97.841
Canyon & Bioassessment	22	LBC	30.296	-97.927
Canyon & Bioassessment &Sediment	42	HHT	30.299	-97.876
Canyon & Bioassessment &Sediment	51	RRT	30.296	-97.851
Canyon & Bioassessment &Sediment	52	Fazio Trib	30.294	-97.852
Canyon & Stormwater	64	SWMP-Lost Creek Subdivision	30.283	-97.842
Canyon Representative (Residential and small buffer)	78	RRC	30.275	-97.840
Canyon Representative (Rural)	68	SSBE	30.277	-97.867
Canyon Representative (Golf) & Bioassessment	63	CRT#1	30.284	-97.852
Canyon Representative (Large Buffer) & Sediment	80	LCR	30.271	-97.831
Canyon & Springs	79	LCW	30.275	-97.836

Appendix F (cont'd)
Barton Creek Report Site Numbers

Study	BC Report #	Site Name	Latitude	Longitude
Pool	1	Pool #1	30.245	-98.126
Pool	10	Pool #2	30.243	-98.011
Pool	20	Pool #4	30.279	-97.942
Pool	24	Pool #5	30.296	-97.926
Pool	43	Pool #6	30.302	-97.868
Pool	56	Pool #7	30.291	-97.849
Pool	74	Pool #8	30.273	-97.844
Pool	81	Pool #9	30.268	-97.823
Pool & Sediment	15	Pool #3	30.270	-97.973
Sediment	87	Barton Ridge Plaza Sed/Filt. Pond	30.234	-97.801
Sediment	89	Campbell's Hole	30.259	-97.784
Sediment	91	Above Pool (Barton Springs)	30.264	-97.773
Sediment	96	Barton Springs Road Inlet Filter	30.264	-97.764
Sediment	98	Barton Creek Mouth	30.267	-97.760
Springs	8	Fitzhugh Spring	30.241	-98.011
Springs	12	SRs2 Jama Spring	30.276	-98.004
Springs	13	SRs1 Hollman Hollow Spring	30.276	-98.004
Springs	14	SRs7 Chalk Knob Spring	30.272	-97.986
Springs	17	SRs11 Palmetto Spring	30.273	-97.967
Springs	32	SW Parkway Spring	30.279	-97.901
Springs	35	Barton Creek West (Scenic B)	30.297	-97.894
Springs	36	Grotto Spring	30.296	-97.894
Springs	37	Barton Creek West Footbridge	30.296	-97.894
Springs	38	Barton Scenic Brook Spring	30.303	-97.889
Springs	39	Uplands 1a-Quonset Spring	30.286	-97.889
Springs	44	Pool #6 Spring	30.304	-97.869
Springs	55	LJ Spring	30.291	-97.851
Springs	62	Crenshaw Spring	30.286	-97.850
Springs	72	Lost Creek Spring A	30.273	-97.844
Springs	73	Lost Creek Spring B	30.273	-97.844
Springs	76	Lost Creek Bridge Spring	30.275	-97.841
Springs	82	Backdoor Spring	30.260	-97.824
Springs	92	Barton Springs	30.263	-97.771
Springs	93	Eliza Spring	30.264	-97.771
Springs	95	Old Mill (SunkenGardens)	30.263	-97.768
Springs	97	Cold Spring	30.270	-97.781
Stormwater	21	SWMP-Windango @Hwy 71	30.291	-97.932
Stormwater	83	SWMP-Travis Country Channel	30.253	-97.828
Stormwater	84	SWMP-Travis Country Pipe	30.249	-97.823
Stormwater	85	SWMP-Hwy BMP #5	30.239	-97.819
Stormwater	86	SWMP-Hwy BMP #6	30.239	-97.818
Stormwater	90	SWMP-Spyglass Dr. Office Site	30.262	-97.785

Appendix G – Monitoring Priority Recommendation Evaluation

Appendix G
Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Term Recommendation	Information Expectations	Monitoring Goal	Data Evaluation Methodology	Status
7.1 Groundwater Study Recommendations				
7.1.1 Barton Springs Contributing Zone				
a. Continue to identify and monitor springs at several levels of watershed development	How are current levels of urbanization affecting groundwater quality?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians. Geochemical analysis techniques	Recommended for Immediate Implementation
b. Locate and monitor new springs in developing watersheds	How is continued urbanization affecting groundwater quality throughout the development process?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time. Geochemical analysis techniques	Recommended for Immediate Implementation
c. Increase monitoring of springs in effluent irrigation areas.	How is land application affecting groundwater quality?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians. Geochemical analysis techniques	Recommended for Immediate Implementation
d. Continue flow monitoring in various land use watersheds	How are current levels of urbanization affecting groundwater quantity?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Not Recommended for Implementation
e. Implement tracer studies in alternative wastewater disposal sites.	How are varying ww disposal methods affecting pollutant transport and attenuation?	Determine time of travel and flow pathway.	Dye tracer recovery and timing	Not Recommended for Implementation
7.1.2 Barton Springs Recharge Zone				
a. Continue biweekly monitoring of Barton Springs - TSS and Nutrients only	Is BS water quality changing over time?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time. Geochemical analysis techniques	Recommended for Immediate Implementation
b. Continue Barton Springs and other spring water quality monitoring	Is BS water quality changing over time?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time. Geochemical analysis techniques	Recommended for Immediate Implementation
c. Monitor suspended sediment quality in Barton and other springs	Are suspended solids transporting pollutants through the aquifer?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time. Geochemical analysis techniques	Recommended for Immediate Implementation
d. Increase heavy metals analysis in Barton and other springs.	Is water quality in spring discharges changing over time?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time. Geochemical analysis techniques	Recommended for Immediate Implementation
e. Increase multiparameter datalogging usage in springs	What are baseline conditions and responses to storm events in contributing watersheds?	Determine baseline field data and dynamics of springs responses to storm events	Time series analysis	Recommended for Immediate Implementation
f. Continue storm water sampling at Barton Springs and monitor at Old Mill, Eliza, Cold, and Backdoor Springs	How is spring water quality affected by storm events?	Determine baseline data for storm responses at springs.	Summary statistics and geochemical analysis techniques	Recommended for Immediate Implementation
g. Monitor water quality of springs during drawdown of pool	How does water from "bad water line" affect spring water quality during drought and pool maintenance?	Determine chemical classification of water during drawdown.	Summary statistics, time series data, and geochemical analysis techniques	Recommended for Immediate Implementation
h. Monitor recharge zone flows in Barton, Eanes, and other creeks	What is distribution of recharge in contributing creeks by reach?	Determine creek yield and reach variation.	Summary statistics and correlation with watershed variables.	Recommended for Implementation within 5 Years

Appendix G
Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Form Recommendation	Information Expectations	Monitoring Goal	Data Evaluation Methodology	Status
i. Continue with tracer studies in BSEA Conservation District	What are flow paths and migration rates in the aquifer?	Determine time of travel and flow pathway.	Time series analysis and summary statistics of dye recovery	Recommended for Immediate Implementation
j. Locate new well to monitor water levels BSEA near Barton Springs	Can better estimates of BS flow be obtained by using a different well not affected by maintenance?	Improve accuracy and availability of discharge data from Barton Springs	Correlation of water levels with BS discharge and pool drawdown.	Recommended for Implementation within 5 Years
k. Deepen USGS monitoring well YD-58-42-217 (Loop 360)	Can well monitoring be improved during low flow conditions?	Improve data availability and quality from this well	Additional data for evaluation using summary statistics and geochemical analysis techniques	Recommended for Immediate Implementation
l. Estimate aquifer water levels in periods where flow continues in Old Mill and Eliza Springs while Barton Springs Pool is lowered	At what aquifer levels will pump-over from pool be needed to keep Old Mill and Eliza viable salamander habitat?	Minimize threats to salamander populations	Analyze discharge rates and pool drawdowns	Recommended for Implementation within 5 Years
7.2 Surfacewater Monitoring Recommendations				
7.2.1 Barton Creek Mainstem				
a. Continue quarterly monitoring of mainstem pools for water chemistry and percent algae cover.	How is continued urbanization affecting BC water chemistry and algae growth?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Recommended for Immediate Implementation
b.. Monitor 2 Pools at Barton Creek Blvd. Lost Creek Blvd., Pool 8, or Camp Craft Access with datsonde	What are frequency and magnitude of transient, potentially cumulative water quality impacts from storm flow at mainstem stations?	Document dynamics of pools and look for transient events with cumulative effects.	Summary statistics, time series data, and comparisons of sites.	Recommended for Immediate Implementation
7.2.2 Barton Creek Tributaries				
a. Compare water quality differences between other watershed attributes such as percent impervious cover, presence of water quality controls, and other ordinance driven characteristics.	Can differences in BC tributary water quality be attributed to varying buffer width, impervious cover, or water quality controls?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Recommended for Immediate Implementation
b. Continue to monit[illegible]taries to Barton Creek quarterly	How is continued urbanization and wastewater disposal affecting tributary water quality ?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Recommended for Immediate Implementation
c. Monitor tributaries which are currently undeveloped, but planned for development on a weekly basis	How is increasing urbanization with regulatory controls affect baseflow water quality in developing tributaries?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
7.2.3 Citizen Monitoring				
a. Coordinate regional Citizens Monitoring in the Austin Area.	How does BC water quality compare to other Central Texas streams.	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
b. Monitor water chemistry and calculate annual index of water quality for public information from regional citizen monitoring.	How does BC water quality compare to other Central Texas streams.	Detect differences between sites and site groups. Evaluate EII scores and compare to other creeks.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians. Relative EII score	Recommended for Immediate Implementation
7.2.4 Stormwater Monitoring				

Appendix G
Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Form Recommendation	Information Expectations	Monitoring Goal	Data Evaluation Methodology	Status
a. Increase stormwater monitoring at mainstem USGS-type stations Hwy 71, Loop 360, and Lost Creek to 2 storms annually (6 grabs per storm).	Can definition of spatial differences be improved through increasing sample frequency.?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Recommended for Immediate Implementation
b. Install one new USGS-type station between Lost Creek MUD and BCEZ (6 storms w/6 grabs)	How is continued urbanization affecting mainstem water chemistry ?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Not Recommended for Implementation
c. Monitor undeveloped but developing streams in the Exemption Zone (3 storms per year)	How is continued urbanization affecting tributary water chemistry ?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
7.2.5 Recommendations For Sediment Monitoring				
a.. Monitor sediment quarterly for total petroleum hydrocarbons.	Are organic contaminants accumulating in BC sediment?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
b. Monitor sediment for full suite of toxic constituents, including pesticides using standardized study design practices and sediment traps.	Can improved methods provide definition of causes for sediment contamination?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
b. Develop site specific sediment quality criteria (SQC) for organics and SEM/AVS ratios for metals.	Can current TNRCC/EPA regulatory protocols be used to define appropriate sediment standards for BC?	Comparison of BC to regulatory standard criteria.	Comparison of means	Not Recommended for Implementation
c. Monitor using bioassays in addition to chemical analysis	Are current regulatory protocols for setting sediment criteria protective of aquatic life in BC?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Not Recommended for Implementation
7.3 Bioassessment Monitoring Recommendations				
7.3.1 Biomonitoring Recommendations for Barton Creek				Underway on a planning level as part of City-Wide Masterplan
a. Monitor benthic macroinvertebrates, diatoms, and percent algae cover on a quarterly basis at the 10 surfacewater sites along Barton Creek	How is continued urbanization affecting BC aquatic biology?	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Recommended for Immediate Implementation
b. Develop an appropriate ecological model for the Central Texas Hill Country ecoregion.	What is appropriate levels of regulatory control necessary to protect BC aquatic biology?	Determine the most appropriate model.	Multiple regression of benthic and diatom data	Recommended for Implementation within 5 Years
7.3.2 Future Monitoring Recommendations for the Barton Springs Salamander				
a. Continue monthly surveys of salamander populations and the general biota of the springs long-term.	How is continued watershed urbanization affecting salamander population and spring habitat?	Determine trends in salamander counts and water quality as development occurs over time	Regression of salamander counts versus time and other available variables	Recommended for Immediate Implementation
b. Survey Eliza and Old Mill Springs monthly	How is continued watershed urbanization affecting salamander population and spring habitat?	Determine trends in water quality as development occurs over time	Regression of salamander counts versus time and other available variables	Recommended for Immediate Implementation

Appendix G
Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Term Recommendation	*Information Expectations*	*Monitoring Goal*	*Data Evaluation Methodology*	*Status*
c. Monitor aquifer salamander populations by using drift nets at all major spring outlets within the Barton Creek watershed.	Can estimate of salamander population and status from visual reconnaissance be improved through alternative sampling techniques?	Determine population from multiple methods	Comparison of technique by means	Recommended for Implementation within 5 Years
7.4 Recommendations from Surface Water Modeling Study				
a. Monitor channel erosion parameters for model calibration	Can monitoring data be used with different model formulation to account for erosional load?	Evaluate deterministic parameters in erosion models	Means of parameters over data set.	Underway on a planning level as part of City-Wide Masterplan
b. Monitor basin rainfall using rain gages installed upstream of Highway 71 near the border of the City's ETJ	Can more accurate rainfall data improve calibration of water quantity model.	Hydrological analysis techniques	Means and summary statistics and spatial comparison of rain gages	Recommended for Implementation within 5 Years
c. Monitor pan evaporation to provide a backup source of data to the National Weather Service which has proved to be inconsistent in the past.	Can more accurate evaporation data improve calibration of water quantity model.	Hydrological analysis techniques	Means and summary statistics and spatial comparison of evaporation gages	Recommended for Implementation within 5 Years
d. Monitor flow and water quality using station just upstream of Barton Springs Pool possibly at the location of the current USGS discharge measurement station 8155400.	Can more accurate flow and water quality data in the lower watershed above spring influence improve calibration of water quantity model.	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Immediate Implementation
e. Increase frequency and duration of sampling during storm events.	Can more refined storm water quality monitoring allow a predictive model formulation to be calibrated.	Evaluate deterministic parameters in water quality models	Means of parameters over data set	Not Recommended for Implementation
f. Convert Flood Early Warning gages in the watershed with depth monitoring capabilities to flow rate monitoring by developing accurate rating curves.	Can more detailed subwatershed flow monitoring provide a better quantity calibration.	Evaluate deterministic parameters in water quantity models	Means of parameters over data set	Not Recommended for Implementation
g. Increase rainfall water quality monitoring stations and frequency	closure of pollutant balance and better input to model.	Hydrological analysis techniques	Means and summary statistics and spatial comparison of rain gages	Recommended for Immediate Implementation
7.5 Recommendations from Groundwater Modeling Study				Recommended for Immediate Implementation
a. Install a monitoring site on Barton Creek just upstream from Barton Springs Pool.	the lower watershed above spring influence improve calibration of water quantity model.	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Not Recommended for Implementation
b. Move Williamson Creek monitoring site to the upstream edge of the recharge zone.	What is the subwatershed impact of development on the aquifer.	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Not Recommended for Implementation
c. Monitor Little Bear Creek temporarily.	What is the subwatershed impact of development on the aquifer.	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Not Recommended for Implementation
d. Monitor flows intensively to determine recharge characteristics for specific stream segments within the recharge zone	What is distribution of recharge in contributing creeks by reach?	Determine mean creek yields by reach and compare reaches	Summary statistics and multiple regression with watershed variables	Recommended for Implementation within 5 Years
e. Use a well located farther away from the pool to estimate Barton Springs flow.	Can better estimates of BS flow be obtained by using a different well not affected by maintenance?	Determine BS flows	Summary statistics and comparisons from earlier data based on different well.	Recommended for Implementation within 5 Years
f. Increase frequency of water quality sampling in wells and at Barton Springs.	Is groundwater water quality changing over time, and is model accurately predicting this change?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Recommended for Implementation within 5 Years

Appendix G
Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Form Recommendation	Information Expectations	Monitoring Goal	Data Evaluation Methodology	Status
g. Monitor flow paths, travel times, and other pollutant transport properties of Edwards Aquifer.	How are varying ww disposal methods affecting pollutant transport and attenuation?	Determine travel times and flow paths	Time series and summary statistics for tracer recovery	Recommended for Immediate Implementation
7.8 Recommendations from the Water Quality Retrofit Masterplan				
a. Continue golf study risk assessment for effluent irrigation and fertilizer application evaluations to determine threat to aquifer	NA	NA	NA	Attempted, but no participation by watershed golf courses
b. Define existing water quality and creek degradation in the BSZ and the beneficial uses of the watersheds to increase public awareness of the uniqueness of the system.	NA	NA	NA	Publication of this report documents previous efforts and coordinates plan for further definition.
c. Quantify instream channel erosion and construction load reductions anticipated from structural water quality controls.	NA	NA	NA	Initiated through consultant contract and masterplan assessments.
d. Model baseflow reduction from impervious cover introduction and impact of large numbers of detention facilities on basin hydrology.	NA	NA	NA	Ongoing through masterplan interlocal agreement.
e. Complete a detailed assessment of Williamson Creek.	Existing monitoring sufficient for current priorities.	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Existing monitoring sufficient for current priorities.
f. Refine septic system evaluation including sampling program and distribution of failure types in the watershed. Make better estimation of septic tank loads	NA	NA	NA	AWWS monitored conventional systems, no inventory of failure types, Barrett/Kam estimated loads
g. Complete retrofit cost evaluation for replacing septic systems in the BSZ.	NA	NA	NA	Regulatory jurisdiction precludes implementation, not a current analysis priority.
h. Conduct intensive monitoring of stormflow and baseflow recession following significant event in Barton Creek or others in BSZ. Correlate dropping concentrations in baseflow with time or flow rate or both to understand the basin operation.	NA	NA	NA	Recommended for Immediate Implementation
i. Examine aquifer degradation threshold to define the limit of irreparable of significant degradation.	What are the quantifiable conditions of degradation beyond which uses such as Barton Springs pool or drinking water well use is impaired?	Determine trends in water quality as development occurs over time	Linear regression fit of water chemistry data versus time	Not Recommended for Implementation
j. Evaluate water quality control maintenance realities including current levels and costs for long term maintenance program and water quality impacts of maintenance failures.	NA	NA	NA	TNRCC inventory of maintenance at existing ponds has been drafted, BMP grant evaluation of maintenance frequencies, masterplan evaluation of loading impacts of maintenance failures.
k. Evaluate recharge and springs flows through the BSEA system to define recharge flows better	NA	NA	NA	Not Recommended for Implementation
l. Refine nitrogen accounting in the Barton springs system and reconcile nitrogen balance.	NA	NA	NA	Barrett and Kam refined nitrogen accounting and reconciled nitrogen balance to existing data on sources.

Barton Creek Watershed Monitoring Recommendation Priority Evaluation

Short Form Recommendation	Information Expectations	Monitoring Goal	Data Evaluation Methodology	Status
m. Add septic system dominated watersheds to canyon study to define level of increase in baseflow nitrogen from these systems	Implemented in Canyon Study documented in this report.	Detect differences between sites and site groups.	Parametric ANOVA if normally distributed or non-parametric Kruskal-Wallis Test for comparison of means and Median Analysis for comparison of medians.	Implemented in Canyon Study documented in this report.
n. Perform additional modeling of golf courses and lawns to improve nitrogen accounting	NA	NA	NA	Ongoing through EPIC modeling for City courses may be used in BC courses in permit review of effluent irrigation.
o. Asses pulse loadings and shape of probability distribution of loadings to determine affect on assessment of spatial and temporal averaging.	NA	NA	NA	Datasonde deployment first step in understanding pulse loadings and PD of loadings. Barrett modeled pulse loadings in gross manner.
p. Assess COA water quality monitoring program aimed at defining future efforts in support of ordinances, models , and tracking the health of the watershed.	NA	NA	NA	Review of BC monitoring by COA completed with documentation in this report. Additional review underway as part of the City-wide masterplan.
q.Perform water quality modeling capable of integrating development related loads, septic systems, and BMP implementation in prediction of changes in aquifer pollutant concentrations, creek water quality and flow patterns, reparian ecology and morphology.	NA	NA	NA	Attempted using SWMM model formulations and concurrent development of groundwater model. No modeling framework integrates all of these factors currently.
r. Studies to support model development would quantify load and concentration associated with development, load apportionment by source, effect of water quality controls, effect of septic tank usage, rangeland management, golf course management.	NA	NA	NA	Load and concentration, load apportionment by source, affect of controls evaluated with loading model. Septic tank evaluated with groundwater model. Golf course ongoing study, Rangeland management potential pilot.

Appendix H – Summary of Statistical Analyses

Appendix H

Analysis Results of Barton Creek Pools Study
Baseflow Conditions

Variable	Number of Observations Pools 1 - 9	Number of Non-Detects	Normality Test on Raw Data									Nonparametric Tests			Multiple Comparison Test (Nonparametric)			
												GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast Test on Ranked Data			
			Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9							
			Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Sites	Pr > F	Sites	Pr > F
Conductivity	18/18/17/17/18/16/15/18/17	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.0001	0.5575	0.4403	0.6975	0.5408	0.0003	0.0083	0.0001	0.0003	0.0005	0.0009	0.0271	8 vs 1-7, 9	0.0074		
TDS	19/20/18/19/19/19/18/17/19	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.2763	0.4479	0.4349	0.6690	0.9257	0.0001	0.0005	0.0001	0.0072	0.0075	0.0097	0.0504	8 vs 1-7, 9	0.0019		
Turbidity	21/19/19/19/21/19/19/18/19	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.0001	0.1357	0.0051	0.0001	0.0002	0.0001	0.0080	0.0732	0.0453	0.0001	0.0002	0.0001	7,9 vs 1-6, 8	0.0003	6 vs 1-5, 7-9	0.0034
TSS	17/17/17/17/17/17/17/17/17	4 / 3 / 5 / 5 / 3 / 7 / 3 / 3 / 2	0.0016	0.0024	0.0065	0.0156	0.0043	0.0001	0.0001	0.0235	0.0018	0.0736	0.0786	0.1618	9 vs 1-8	0.0239	7,9 vs 1-6, 8	0.0571
VSS	17/17/17/17/17/17/17/17	8 / 9 / 12 / 8 / 9 / 14 / 9 / 9 / 9	0.0001	0.0002	0.0001	0.0004	0.0001	0.0001	0.0001	0.0009	0.0001	0.3338	0.3316					
COD	7/6/5/6/12/6/5/12/6	4 / 4 / 3 / 4 / 11 / 5 / 3 / 11 / 4	0.0088	0.0293	0.1809	0.0474	0.0001	0.0001	0.0846	0.0010	0.0028	0.8827	0.8661					
NH3-N	18/19/17/17/19/17/17/19/17	4 / 3 / 2 / 2 / 4 / 3 / 1 / 2 / 1	0.0001	0.0001	0.0003	0.0001	0.0001	0.0007	0.0001	0.0001	0.0001	0.7431	0.7344					
NO2+3-N	14/14/14/14/14/14/14/14/14	2 / 4 / 2 / 1 / 2 / 1 / 2 / 2 / 1	0.0123	0.0008	0.0055	0.0033	0.0051	0.0508	0.0003	0.0001	0.2289	0.0170	0.0214	0.0258	8 vs 1-7, 9	0.0016	7 vs 1-6, 9	0.1828
TKN	15/16/16/16/16/16/16/16/16	4 / 4 / 8 / 4 / 4 / 7 / 1 / 1 / 4	0.1047	0.0310	0.0015	0.0004	0.0575	0.0024	0.1304	0.0072	0.0021	0.2250	0.2265	0.2634	8 vs 1-7, 9	0.0159		
TP	17/17/17/17/17/17/17/17/17	9 / 9 / 7 / 4 / 10 / 10 / 8 / 10 / 8	0.0001	0.0001	0.0001	0.0056	0.0001	0.0001	0.0005	0.0011	0.0001	0.5712	0.5631					
Ortho-P	14/14/14/14/14/14/14/14/14	3 / 12 / 12 / 9 / 14 / 12 / 12 / 14 / 1	0.0001	0.0001	0.0001	0.0001	.	0.0001	0.0001	0.0001	0.0001	0.5097	0.5012					
TOC	0/0/0/0/12/0/12/0/0	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	.	.	.	.	0.0063	.	.	0.0001	.	0.7799	0.7728	0.4241				
F Col	18/18/16/16/18/17/16/17/16	0 / 1 / 0 / 0 / 1 / 2 / 2 / 0 / 2	0.0001	0.0001	0.0001	0.0001	0.0001	0.0005	0.0001	0.0001	0.0010	0.0001	0.0001	0.0038	1 vs 2-9	0.0001		
Flow	5/5/5/5/5/5/5/5/5	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.2216	0.7712	0.2349	0.4910	0.6702	0.7713	0.6127	0.6863	0.9141	0.0026	0.0100	0.0263	1 vs 2-8	0.0003	9 vs 2-8	0.1780

Variable	Number of Observations Pools 1 - 9	Number of Non-Detects	Normality Test on Natural Log of Data									Parametric Test	Multiple Comparison Test (Parametric)			
												GLM on Natural Log of Data	Contrast Test on Natural Log of Data			
			Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9					
			Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Sites	Pr > F	Sites	Pr > F
Conductivity	18/18/17/17/18/16/15/18/17	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.0001	0.2478	0.2583	0.6900	0.5577	0.0001	0.0366	0.0005	0.0029	0.0021	8 vs 1-7, 9	0.0006		
TDS	19/20/18/19/19/19/18/17/19	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.6388	0.1485	0.0789	0.8793	0.7530	0.0003	0.0045	0.0017	0.1395	0.0019	8 vs 1-7, 9	0.0002		
Turbidity	21/19/19/19/21/19/19/18/19	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.0321	0.062	0.8628	0.0063	0.4529	0.8079	0.6770	0.5972	0.1697	0.0001	7,9 vs 1-6, 8	0.0003	6 vs 1-5, 7-9	0.0032
TSS	17/17/17/17/17/17/17/17/17	4 / 3 / 5 / 5 / 3 / 7 / 3 / 3 / 2	0.1003	0.1942	0.0106	0.0181	0.1468	0.0042	0.3198	0.4181	0.7150	0.0435	9 vs 1-8	0.0134	7,9 vs 1-6, 8	0.0278
VSS	17/17/17/17/17/17/17/17	8 / 9 / 12 / 8 / 9 / 14 / 9 / 9 / 9	0.0027	0.0003	0.0001	0.0024	0.0008	0.0001	0.0004	0.0013	0.0012	0.4094				
COD	7/6/5/6/12/6/5/12/6	4 / 4 / 3 / 4 / 11 / 5 / 3 / 11 / 4	0.0252	0.0818	0.4082	0.0334	0.0001	0.0037	0.2930	0.0019	0.0028	0.7783				
NH3-N	18/19/17/17/19/17/17/19/17	4 / 3 / 2 / 2 / 4 / 3 / 1 / 2 / 1	0.0041	0.0714	0.0840	0.0022	0.0060	0.0824	0.0104	0.1073	0.0318	0.9470				
NO2+3-N	14/14/14/14/14/14/14/14/14	2 / 4 / 2 / 1 / 2 / 1 / 2 / 2 / 1	0.7563	0.1445	0.3363	0.7221	0.3900	0.5614	0.7578	0.1647	0.2827	0.0071	8 vs 1-7, 9	0.0003	7 vs 1-6, 9	0.1624
TKN	15/16/16/16/16/16/16/16/16	4 / 4 / 8 / 4 / 4 / 7 / 1 / 1 / 4	0.4546	0.7323	0.0328	0.2119	0.7211	0.3109	0.9972	0.2204	0.8169	0.1832	8 vs 1-7, 9	0.0113		
TP	17/17/17/17/17/17/17/17/17	9 / 9 / 7 / 4 / 10 / 10 / 8 / 10 / 8	0.0013	0.0010	0.0008	0.0146	0.0001	0.0001	0.0011	0.0039	0.0020	0.7593		-		
Ortho-P	14/14/14/14/14/14/14/14/14	3 / 12 / 12 / 9 / 14 / 12 / 12 / 14 / 1	0.0001	0.0001	0.0001	0.0001	.	0.0001	0.0001	0.0001	0.0001	0.7701				
TOC	0/0/0/0/12/0/12/0/0	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	.	.	.	.	0.1161	.	.	0.0015	.	0.9273				
F Col	18/18/16/16/18/17/16/17/16	0 / 1 / 0 / 0 / 1 / 2 / 2 / 0 / 2	0.2068	0.7375	0.2503	0.0409	0.7086	0.5127	0.4865	0.2226	0.1988	0.0001	1 vs 2-9	0.0001		
Flow	5/5/5/5/5/5/5/5/5	0 / 0 / 0 / 0 / 0 / 0 / 0 / 0 / 0	0.4401	0.6341	0.7239	0.5206	0.6290	0.0962	0.4431	0.1924	0.1072	0.0001	1 vs 2-8	0.5554	9 vs 2-8	0.0001

**Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05

***Nonparametric Tests: Ho = No differences. Reject Ho if 'Pr > F' is greater than 0.05.

****Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F'is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Analysis Results of Barton Creek Algae Transect Data
Filamentous Algae = Cladophora, Spirogyra and Other Algae
Total Algae = Filamentous Algae, Carpet Algae, Chara and Nitella
Baseflow Conditions

Variable	Number of Observations	Normality Test on Raw Data									Nonparametric Tests			Multiple Comparison Test (Nonparametric)	
											GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast Test on Ranked Data	
		Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9					
		Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Pools	Pr > F
Filamentous Algae	18/18/18/18/18/18/18/18/18	0.0008	0.0034	0.0001	0.0001	0.0001	0.0001	0.0532	0.0889	0.0001	0.0001	0.0003	0.0004	8 vs others	0.0002
Total Algae	18/18/18/18/18/18/18/18/18	0.1981	0.1337	0.3677	0.2984	0.1153	0.0512	0.1599	0.0461	0.0222	0.6899	0.6813	0.3196	8 vs others	0.1784

Variable	Number of Observations	Normality Test on Natural Log of Data*									Parametric Test	Multiple Comparison Test (Parametric)	
											GLM on Natural Log of Data	Contrast Test on Natural Log of Data	
		Pool 1	Pool 2	Pool 3	Pool 4	Pool 5	Pool 6	Pool 7	Pool 8	Pool 9			
		Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Pools	Pr > F
Filamentous Algae	18/18/18/18/18/18/18/18/18	0.0049	0.0086	0.0001	0.0003	0.0012	0.0037	0.0811	0.1122	0.011	0.0001	8 vs others	0.0001
Total Algae	18/18/18/18/18/18/18/18/18	0.1385	0.1197	0.3227	0.0200	0.2864	0.7656	0.9015	0.2945	0.6923	0.0872	8 vs others	0.1896

*Zero data values in input data set were changed to 0.0001

**Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05

***Nonparametric Tests: Ho =No differences. Reject Ho if 'Pr > F' is greater than 0.05.

****Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F'is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Barton Creek Report
Analysis Results of Barton Creek Canyon Data
All Sites Consolidated into Golf, Residential Rural Groups
Baseflow Conditions

Variable	Number of Observations G/Res/Rur*	Number of Non-Detects G/Res/Rur*	Normality Test** on Raw Data			Nonparametric Tests***			Multiple Comparison Test (Nonparametric)***					
						GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast Test on Ranked Data					
			Golf	Residential	Rural									
			Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	54 / 91 / 43	0 / 0 / 0	0.0006	0.0001	0.1597	0.1910	0.1904	0.1094	Golf vs Res	0.2371	Golf vs Rural	0.5788	Res vs Rural	0.0880
TDS	54 / 92 / 42	0 / 0 / 0	0.0316	0.0321	0.0001	0.0001	0.0001	0.0001	Golf vs Res	0.0001	Golf vs Rural	0.0001	Res vs Rural	0.0001
Turbidity	30 / 66 / 40	3 / 17 / 16	0.0001	0.0001	0.0001	0.0003	0.0004	0.0002	Golf vs Res	0.0012	Golf vs Rural	0.0001	Res vs Rural	0.2219
NH3-N	61 / 94 / 48	20 / 32 / 30	0.0001	0.0001	0.0001	0.0523	0.0530	0.0778	Golf vs Res	0.6743	Golf vs Rural	0.0663	Res vs Rural	0.0174
NO3-N	66 / 99 / 55	4 / 15 / 22	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	Golf vs Res	0.0291	Golf vs Rural	0.0001	Res vs Rural	0.0001
Ortho-P	64 / 97/ 52	3 / 7 / 3	0.0001	0.0001	0.0001	0.2542	0.2532	0.0515	Golf vs Res	0.1402	Golf vs Rural	0.1596	Res vs Rural	0.8843
F Col	20 / 60 / 33	1 / 4 / 2	0.0001	0.0001	0.0001	0.2939	0.2914	0.4927	Golf vs Res	0.5567	Golf vs Rural	0.5091	Res vs Rural	0.1196
TSS	37 / 52 / 19	6 / 16 / 10	0.0001	0.0001	0.0001	0.0049	0.0058	0.0108	Golf vs Res	0.0474	Golf vs Rural	0.0014	Res vs Rural	0.0668
Flow	25 / 42 / 28	2 / 1 / 0	0.0001	0.0001	0.0001	0.0151	0.0166	0.0330	Golf vs Res	0.4388	Golf vs Rural	0.0065	Res vs Rural	0.0216

Variable	Number of Observations G/Res/Rur*	Number of Non-Detects G/Res/Rur*	Normality Test** on Natural Log of Data			Parametric Test****	Multiple Comparison Test (Parametric)***					
						GLM on Natural Log of Data	Contrast Test on Natural Log of Data					
			Golf	Residential	Rural							
			Pr < W	Pr < W	Pr < W	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	54 / 91 / 43	0 / 0 / 0	0.0001	0.0001	0.2329	0.2879	Golf vs Res	0.1184	Golf vs Rural	0.5198	Res vs Rural	0.4578
TDS	54 / 92 / 42	0 / 0 / 0	0.7558	0.9983	0.0165	0.0001	Golf vs Res	0.0001	Golf vs Rural	0.0001	Res vs Rural	0.0001
Turbidity	30 / 66 / 40	3 / 17 / 16	0.1504	0.0001	0.0001	0.0003	Golf vs Res	0.0015	Golf vs Rural	0.0001	Res vs Rural	0.1715
NH3-N	61 / 94 / 48	20 / 32 / 30	0.0001	0.0001	0.0001	0.0370	Golf vs Res	0.8332	Golf vs Rural	0.0215	Res vs Rural	0.0210
NO3-N	66 / 99 / 55	4 / 15 / 22	0.0001	0.0003	0.0001	0.0001	Golf vs Res	0.0231	Golf vs Rural	0.0001	Res vs Rural	0.0001
Ortho-P	64 / 97/ 52	3 / 7 / 3	0.0001	0.0001	0.0020	0.5214	Golf vs Res	0.2629	Golf vs Rural	0.4438	Res vs Rural	0.8272
F Col	20 / 60 / 33	1 / 4 / 2	0.7752	0.0488	0.6162	0.5259	Golf vs Res	0.8058	Golf vs Rural	0.5222	Res vs Rural	0.2597
TSS	37 / 52 / 19	6 / 16 / 10	0.0066	0.0001	0.0004	0.0045	Golf vs Res	0.0413	Golf vs Rural	0.0013	Res vs Rural	0.0713
Flow	25 / 42 / 28	2 / 1 / 0	0.4696	0.2432	0.0341	0.0261	Golf vs Res	0.5105	Golf vs Rural	0.0119	Res vs Rural	0.0295

*G/Res/Rur = Golf / Residential / Rural
**Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05
***Nonparametric Tests: Ho =No differences. Reject Ho if 'Pr > F' is greater than 0.05.
****Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F'is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Barton Creek Report
Analysis Results of Barton Creek Canyon Data
Crenshaw Tributary (Golf), Ringtail Ridge Canyon (Res.) and Short Spring Branch Estates (Rural)
Baseflow Conditions

Variable	Number of Observations CRT1 / RRC / SSBE	Number of Non-Detects CRT1 / RRC / SSBE	Normality Test** on Raw Data			Nonparametric Tests***			Multiple Comparison Test (Nonparametric)***					
						GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast Test on Ranked Data					
			CRT1 - Golf	RRC - Res	SSBE - Rural									
			Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	19 / 17 / 12	0 / 0 / 0	0.1919	0.5772	0.3746	0.0259	0.0296	0.0547	Golf vs Res	0.3240	Golf vs Rural	0.0569	Res vs Rural	0.0076
TDS	19 / 17 / 12	0 / 0 / 0	0.4171	0.1001	0.3157	0.0007	0.0015	0.1137	Golf vs Res	0.0010	Golf vs Rural	0.0012	Res vs Rural	0.7945
Turbidity	16 / 16 / 11	1 / 5 / 6	0.0002	0.0007	0.0023	0.0164	0.0202	0.0289	Golf vs Res	0.0259	Golf vs Rural	0.0083	Res vs Rural	0.4944
NH3-N	21 / 17 / 13	11 / 7 / 6	0.0001	0.0048	0.0001	0.7743	0.7672	0.4251	Golf vs Res	0.7146	Golf vs Rural	0.6848	Res vs Rural	0.4769
NO3-N	23 / 18 / 14	1 / 0 / 6	0.8176	0.9736	0.0001	0.0001	0.0001	0.0001	Golf vs Res	0.0012	Golf vs Rural	0.0001	Res vs Rural	0.0001
Ortho-P	21 / 18 / 13	1 / 1 / 2	0.0002	0.1089	0.0893	0.0022	0.0036	0.0201	Golf vs Res	0.0029	Golf vs Rural	0.0028	Res vs Rural	0.7715
F Col	12 / 16 / 11	0 / 0 / 1	0.0001	0.0001	0.0001	0.0228	0.0273	0.0323	Golf vs Res	0.2957	Golf vs Rural	0.0890	Res vs Rural	0.0064
TSS	10 / 12 / 11	6 / 5 / 7	0.0009	0.0244	0.0001	0.4644	0.4504	0.5352	Golf vs Res	0.4505	Golf vs Rural	0.6688	Res vs Rural	0.2259
Flow	7 / 11 / 9	2 / 1 / 0	0.0001	0.0001	0.0110	0.0155	0.0221	0.0089	Golf vs Res	0.4400	Golf vs Rural	0.0072	Res vs Rural	0.0220

Variable	Number of Observations CRT1 / RRC / SSBE	Number of Non-Detects CRT1 / RRC / SSBE	Normality Test** on Natural Log of Data			Parametric Test****	Multiple Comparison Test (Parametric)****					
						GLM on Natural Log of Data	Contrast Test on Natural Log of Data					
			CRT1 - Golf	RRC - Res	SSBE - Rural							
			Pr < W	Pr < W	Pr < W	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	19 / 17 / 12	0 / 0 / 0	0.1648	0.5703	0.3866	0.0185	Golf vs Res	0.2136	Golf vs Rural	0.0672	Res vs Rural	0.0050
TDS	19 / 17 / 12	0 / 0 / 0	0.6063	0.0160	0.6964	0.0009	Golf vs Res	0.0010	Golf vs Rural	0.0018	Res vs Rural	0.9031
Turbidity	16 / 16 / 11	1 / 5 / 6	0.2616	0.0115	0.0227	0.0116	Golf vs Res	0.0216	Golf vs Rural	0.0057	Res vs Rural	0.4489
NH3-N	21 / 17 / 13	11 / 7 / 6	0.0031	0.0234	0.0030	0.7471	Golf vs Res	0.6796	Golf vs Rural	0.6808	Res vs Rural	0.4483
NO3-N	23 / 18 / 14	1 / 0 / 6	0.0001	0.0545	0.0538	0.0001	Golf vs Res	0.0722	Golf vs Rural	0.0001	Res vs Rural	0.0001
Ortho-P	21 / 18 / 13	1 / 1 / 2	0.0394	0.0677	0.2738	0.0025	Golf vs Res	0.0038	Golf vs Rural	0.0027	Res vs Rural	0.7042
F Col	12 / 16 / 11	0 / 0 / 1	0.6772	0.4745	0.2131	0.0479	Golf vs Res	0.5004	Golf vs Rural	0.0870	Res vs Rural	0.0156
TSS	10 / 12 / 11	6 / 5 / 7	0.0038	0.0186	0.0007	0.4037	Golf vs Res	0.4115	Golf vs Rural	0.6406	Res vs Rural	0.1878
Flow	7 / 11 / 9	2 / 1 / 0	0.7977	0.8617	0.3605	0.0114	Golf vs Res	0.4434	Golf vs Rural	0.0055	Res vs Rural	0.0165

**Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05
***Nonparametric Tests: Ho =No differences. Reject Ho if 'Pr > F' is greater than 0.05.
****Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F' is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Analysis Results of Barton Creek Canyons Study
Crenshaw Tributary (Golf), Ringtail Ridge Canyon (Res.), and Short Springs Branch Estates (Rural)
Stormflow Conditions

Variable	Number of Observations CRT1 / RRC / SSBE	Number of Non-Detects CRT1 / RRC / SSBE	Normality Test* Raw Data			Nonparametric Tests**			Multiple Comparison Test (Nonparametric)**					
						GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast Test on Ranked Data					
			CRT1	RRC	SSBE									
			Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	5 / 5 / 4	0 / 0 / 0	0.2683	1.0000	0.0001	0.0913	0.1009	0.0617	Golf vs Res	0.1506	Golf vs Rural	0.3640	Res vs Rural	0.0350
TDS	5 / 5 / 4	0 / 0 / 0	0.8446	0.8045	0.6692	0.0232	0.4000	0.2484	Golf vs Res	0.0643	Golf vs Rural	0.2228	Res vs Rural	0.0080
Turbidity	5 / 5 / 4	1 / 1 / 1	0.0132	0.0025	0.5418	0.2739	0.2558	0.2484	Golf vs Res	0.7889	Golf vs Rural	0.1342	Res vs Rural	0.2016
NH3-N	5 / 5 / 4	0 / 0 / 0	0.3071	0.0347	0.0460	0.3959	0.3650	0.5220	Golf vs Res	0.4180	Golf vs Rural	0.1873	Res vs Rural	0.5523
NO3-N	5 / 5 / 4	0 / 0 / 0	0.1799	0.7818	0.3639	0.0001	0.0044	0.0140	Golf vs Res	0.0031	Golf vs Rural	0.0001	Res vs Rural	0.0026
Ortho-P	5 / 5 / 4	0 / 0 / 1	0.0010	0.0339	0.9381	0.0432	0.0591	0.0140	Golf vs Res	0.2203	Golf vs Rural	0.0142	Res vs Rural	0.1202
F Col	3 / 4 / 3	0 / 0 / 0	0.5055	0.0153	0.2304	0.3697	0.3284	0.1423	Golf vs Res	0.8598	Golf vs Rural	0.2128	Res vs Rural	0.2406
TSS	2 / 3 / 3	0 / 1 / 1	1.0000	0.0279	0.9705	0.9673	0.9548	0.7470	Golf vs Res	0.8312	Golf vs Rural	0.9756	Res vs Rural	0.8381
Flow	1 / 3 / 2	0 / 0 / 0	.	0.0338	1.0000	0.6526	0.5385	0.2494	Golf vs Res	0.6199	Golf vs Rural	0.4017	Res vs Rural	0.5849

Variable	Number of Observations CRT / RRC / SSBE	Number of Non-Detects CRT1 / RRC / SSBE	Normality Test* on Natural Log of Data			Parametric Test***	Multiple Comparison Test (Parametric)***					
						GLM on Natural Log of Data	Contrast Test on Natural Log of Data					
			CRT1	RRC	SSBE							
			Pr < W	Pr < W	Pr < W	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	5 / 5 / 4	0 / 0 / 0	0.2611	1.0000	0.0001	0.0740	Golf vs Res	0.1618	Golf vs Rural	0.2765	Res vs Rural	0.0266
TDS	5 / 5 / 4	0 / 0 / 0	0.9354	0.2242	0.5627	0.0726	Golf vs Res	0.0707	Golf vs Rural	0.6202	Res vs Rural	0.0355
Turbidity	5 / 5 / 4	1 / 1 / 1	0.7630	0.9279	0.8903	0.3473	Golf vs Res	0.9048	Golf vs Rural	0.1890	Res vs Rural	0.2253
NH3-N	5 / 5 / 4	0 / 0 / 0	0.2207	0.4483	0.2523	0.4635	Golf vs Res	0.5099	Golf vs Rural	0.2263	Res vs Rural	0.5355
NO3-N	5 / 5 / 4	0 / 0 / 0	0.2278	0.6901	0.3484	0.0001	Golf vs Res	0.0143	Golf vs Rural	0.0001	Res vs Rural	0.0001
Ortho-P	5 / 5 / 4	0 / 0 / 1	0.0552	0.2101	0.3348	0.1262	Golf vs Res	0.4043	Golf vs Rural	0.0474	Res vs Rural	0.1850
F Col	3 / 4 / 3	0 / 0 / 0	0.1206	0.6920	0.7547	0.2961	Golf vs Res	0.8890	Golf vs Rural	0.2162	Res vs Rural	0.1541
TSS	2 / 3 / 3	0 / 1 / 1	1.0000	0.3022	0.5221	0.9620	Golf vs Res	0.8762	Golf vs Rural	0.9374	Res vs Rural	0.7939
Flow	1 / 3 / 2	0 / 0 / 0	.	0.4062	1.0000	0.5303	Golf vs Res	0.5533	Golf vs Rural	0.3082	Res vs Rural	0.4818

*Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05

**Nonparametric Tests: Ho =No differences. Reject Ho if 'Pr > F' is greater than 0.05.

***Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F'is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Analysis Results of Barton Creek Canyons Study
All Sites Consolidated into R, RS, RC, GEI REI
Baseflow Conditions

Variable	Number of Observations GEI/RC/REI/RS/R*	Number of Non-Detects GEI/RC/REI/RS/R*	Normality Test* on Raw Data					Nonparametric Tests			Multiple Comparison Test (Nonparametric)**							
								GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data	Contrast on Ranked Data							
			GEI	RC	REI	RS	R											
			Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Pr > CHISQ	Pr > CHISQ	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	54 / 48 / 17 / 26 / 43	0 / 0 / 0 / 0 / 0	0.0006	0.0024	0.4883	0.0021	0.1597	0.2964	0.2949	0.2244	Rural vs GEI	0.5792	Rural vs RC	0.3199	Rural vs REI	0.2777	Rural vs RS	0.0380
TDS	54 / 49 / 17 / 26 / 42	0 / 0 / 0 / 0 / 0	0.0316	0.6339	0.7577	0.0212	0.0001	0.0001	0.0001	0.0001	Rural vs GEI	0.0001	Rural vs RC	0.0001	Rural vs REI	0.0001	Rural vs RS	0.0001
Turbidity	30 / 40 / 12 / 14 / 40	3 / 11 / 4 / 2 / 16	0.0001	0.0001	0.0001	0.0336	0.0001	0.0004	0.0007	0.0001	Rural vs GEI	0.0001	Rural vs RC	0.1032	Rural vs REI	0.3733	Rural vs RS	0.2318
NH3-N	61 / 48 / 17 / 29 / 48	20 / 17 / 5 / 10 / 30	0.0001	0.0001	0.0001	0.0001	0.0001	0.1017	0.1030	0.1138	Rural vs GEI	0.0664	Rural vs RC	0.0079	Rural vs REI	0.1384	Rural vs RS	0.3372
NO3-N	66 / 51 / 17 / 31 / 55	4 / 9 / 3 / 3 / 22	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	Rural vs GEI	0.0001	Rural vs RC	0.0001	Rural vs REI	0.0001	Rural vs RS	0.1139
Ortho-P	64 / 49 / 17 / 31 / 52	3 / 4 / 0 / 3 / 3	0.0001	0.0061	0.0001	0.0001	0.0001	0.0955	0.0969	0.0239	Rural vs GEI	0.1565	Rural vs RC	0.3347	Rural vs REI	0.5705	Rural vs RS	0.1701
F Col	23 / 43 / 11 / 6 / 33	1 / 1 / 1 / 2 / 2	0.0001	0.0001	0.0004	0.0001	0.0001	0.0661	0.0692	0.0805	Rural vs GEI	0.5006	Rural vs RC	0.0442	Rural vs REI	0.2552	Rural vs RS	0.1535
TSS	37 / 35 / 4 / 13 / 19	6 / 15 / 0 / 1 / 10	0.0001	0.0001	0.9332	0.0021	0.0001	0.0025	0.0036	0.0244	Rural vs GEI	0.0011	Rural vs RC	0.3424	Rural vs REI	0.0392	Rural vs RS	0.0105
Flow	25 / 18 / 11 / 13 / 28	2 / 1 / 0 / 0 / 0	0.0001	0.0001	0.0005	0.0001	0.0001	0.0163	0.0193	0.0750	Rural vs GEI	0.0060	Rural vs RC	0.0056	Rural vs REI	0.7732	Rural vs RS	0.0837

Variable	Number of Observations GEI/RC/REI/RS/R	Number of Non-Detects GEI/RC/REI/RS/R	Normality Test* on Natural Log of Data					Parametric Test**	Multiple Comparison Test (Parametric)***							
								GLM on Natural Log of Data	Contrast Test on Natural Log of Data							
			GEI	RC	REI	RS	R									
			Pr < W	Pr < W	Pr < W	Pr < W	Pr < W	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F	Sites	Pr > F
pH	54 / 48 / 17 / 26 / 43	0 / 0 / 0 / 0 / 0	0.0001	0.001	0.4246	0.0014	0.2329	0.4638	Rural vs GEI	0.5209	Rural vs RC	0.8500	Rural vs REI	0.5442	Rural vs RS	0.2389
TDS	54 / 49 / 17 / 26 / 42	0 / 0 / 0 / 0 / 0	0.7558	0.5544	0.2934	0.4966	0.0165	0.0001	Rural vs GEI	0.0001	Rural vs RC	0.0001	Rural vs REI	0.0001	Rural vs RS	0.0003
Turbidity	30 / 40 / 12 / 14 / 40	3 / 11 / 4 / 2 / 16	0.1504	0.0001	0.0025	0.1630	0.0001	0.0004	Rural vs GEI	0.0001	Rural vs RC	0.0723	Rural vs REI	0.4274	Rural vs RS	0.2271
NH3-N	61 / 48 / 17 / 29 / 48	20 / 17 / 5 / 10 / 30	0.0001	0.0001	0.0001	0.0001	0.0001	0.1302	Rural vs GEI	0.0219	Rural vs RC	0.0184	Rural vs REI	0.2129	Rural vs RS	0.1716
NO3-N	66 / 51 / 17 / 31 / 55	4 / 9 / 3 / 3 / 22	0.0001	0.0001	0.0512	0.1201	0.0001	0.0001	Rural vs GEI	0.0001	Rural vs RC	0.0001	Rural vs REI	0.0004	Rural vs RS	0.3390
Ortho-P	64 / 49 / 17 / 31 / 52	3 / 4 / 0 / 3 / 3	0.0001	0.0001	0.0327	0.4102	0.0020	0.1641	Rural vs GEI	0.4403	Rural vs RC	0.6511	Rural vs REI	0.4683	Rural vs RS	0.1024
F Col	23 / 43 / 11 / 6 / 33	1 / 1 / 1 / 2 / 2	0.7752	0.6218	0.3937	0.4079	0.6162	0.0574	Rural vs GEI	0.5109	Rural vs RC	0.0859	Rural vs REI	0.4471	Rural vs RS	0.0614
TSS	37 / 35 / 4 / 13 / 19	6 / 15 / 0 / 1 / 10	0.0066	0.0001	0.3677	0.9125	0.0004	0.0026	Rural vs GEI	0.0011	Rural vs RC	0.3534	Rural vs REI	0.0630	Rural vs RS	0.0093
Flow	25 / 18 / 11 / 13 / 28	2 / 1 / 0 / 0 / 0	0.4696	0.6562	0.3371	0.4338	0.0341	0.0294	Rural vs GEI	0.0112	Rural vs RC	0.0073	Rural vs REI	0.7676	Rural vs RS	0.1239

GEI - Golf Effluent Irrigated
RC - Residential on Central
REI - Residential Effluent Irrigated
RS - Residential Septic
R - Rural

*Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05
**Nonparametric Tests: Ho = No differences. Reject Ho if 'Pr > F' is greater than 0.05.
***Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F' is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix H

Analysis Results of Barton Creek Canyon Data
Lost Creek Residential (LCR) and Ringtail Ridge Canyon (RRC)
Residential Sites
Baseflow Conditions

Variable	Number of Observations	Number of Non-Detects	Normality Test* on Raw Data		Nonparametric Tests**			
					GLM on Ranked Data	GLM on Ranked Data	Kruskal-Wallis Test on Raw Data	Median Analysis on Raw Data
			LCR	RRC				
	LCR / RRC	LCR / RRC	Pr < W	Pr < W	Pr > F	Pr > F	Pr > CHISQ	Pr > CHISQ
pH	13 / 17	0 / 0	0.4987	0.5772	0.0001	0.0001	0.0004	0.0005
TDS	13 / 17	0 / 0	0.5745	0.1001	0.4737	0.4353	0.4256	0.2772
Turbidity	11 / 16	3 / 5	0.1400	0.0007	0.1729	0.2418	0.4256	0.2772
NH3-N	13 / 17	4 / 7	0.0003	0.0048	0.8580	0.8836	0.8806	0.9561
NO3-N	13 / 18	5 / 0	0.0001	0.9736	0.0001	0.0001	0.0001	0.0001
Ortho-P	13 / 18	1 / 1	0.3607	0.1089	0.3209	0.3578	0.3491	0.7753
F Col	12 / 16	1 / 0	0.0001	0.0001	0.9428	0.1401	0.1372	0.1336
TSS	9 / 12	3 / 5	0.0031	0.0244	0.7772	0.7782	0.7699	0.2679
Flow	2 / 11	0 / 1	1.0000	0.0001	0.6198	0.5766	0.5537	0.1106

Variable	Number of Observations	Number of Non-Detects	Normality Test* on Natural Log of Data		Parametric Test***
					GLM on Natural Log of Data
			LCR	RRC	
	LCR / RRC	LCR / RRC	Pr < W	Pr < W	Pr > F
pH	13 / 17	0 / 0	0.5957	0.5703	0.0001
TDS	13 / 17	0 / 0	0.3607	0.0160	0.5435
Turbidity	11 / 16	3 / 5	0.0546	0.0115	0.2145
NH3-N	13 / 17	4 / 7	0.1532	0.0234	0.8828
NO3-N	13 / 18	5 / 0	0.4526	0.0545	0.0001
Ortho-P	13 / 18	1 / 1	0.0273	0.0677	0.3269
F Col	12 / 16	1 / 0	0.8226	0.4745	0.1177
TSS	9 / 12	3 / 5	0.3018	0.0186	0.8961
Flow	2 / 11	0 / 1	1.0000	0.8617	0.6088

*Normality Test = Shapiro and Wilk Test: Ho = The population has a normal distribution. Reject Ho if 'Pr < W' is less than or equal to 0.05
**Nonparametric Tests: Ho =No differences. Reject Ho if 'Pr > F' is greater than 0.05.
***Parametric Test: Ho = No differences between means. Reject Ho if 'Pr > F'is greater than 0.05.

Source: COA / Drainage Utility Department

Appendix I – Endangered Species Listing Documentation for Barton Springs Salamander

DEPARTMENT OF THE INTERIOR

Fish and Wildlife Service

50 CFR Part 17

RIN 1018–AC22

Endangered and Threatened Wildlife and Plants; Final Rule To List the Barton Springs Salamander as Endangered

AGENCY: Fish and Wildlife Service, Interior.

ACTION: Final rule.

SUMMARY: The Fish and Wildlife Service (Service) determines the Barton Springs salamander (*Eurycea sosorum*) to be an endangered species pursuant to the Endangered Species Act of 1973, as amended (Act). The Barton Springs salamander is known only from Barton Springs in Zilker Park, Austin, Travis County, Texas. The primary threats to this species are degradation of the quality and quantity of water that feeds Barton Springs due to urban expansion over the Barton Springs watershed. Also of concern is disturbance to the salamander's surface habitat in the pools where it occurs. This action implements Federal protection provided by the Act for the Barton Springs salamander.

EFFECTIVE DATE: May 30, 1997.

ADDRESSES: The complete file for this rule is available for inspection, by appointment, during normal business hours at the Ecological Services Field Office, U.S. Fish and Wildlife Service, 10711 Burnet Road, Suite 200, Austin, Texas 78758.

FOR FURTHER INFORMATION CONTACT: Lisa O'Donnell, Fish and Wildlife Biologist (see **ADDRESSES** section) (telephone: 512/490–0057; facsimile (512/490-0974)).

SUPPLEMENTARY INFORMATION:

Background

The Service determines the Barton Springs salamander (*Eurycea sosorum*) to be an endangered species, under the authority of the Endangered Species Act (Act) (16 U.S.C. 1531 *et seq.*). The Barton Springs salamander is entirely aquatic and neotenic (meaning it does not metamorphose into a terrestrial form and retains its bright red external gills throughout life) and depends on a constant supply of clean, flowing water from Barton Springs. Adults attain an average length of 6.35 centimeters (cm) (2.5 inches (in)). This species is slender, with slightly elongate limbs and reduced eyes. Dorsal coloration varies from pale purplish-brown or gray to yellowish-cream. Irregular spacing of dorsal pigments and pigment gaps results in a mottled, "salt and pepper" pattern (Sweet 1978, Chippindale *et al.* 1993a).

The Barton Springs salamander was first collected from Barton Springs Pool in 1946 by Bryce Brown and Alvin Flury (Chippindale *et al.* 1993a,b). Although he did not publish a formal description, Dr. Samuel Sweet (University of California at Santa Barbara) was the first to recognize the Barton Springs salamander as distinct from other central Texas *Eurycea* salamanders based on its restricted distribution and unique morphological and skeletal characteristics (such as its reduced eyes, elongate limbs, dorsal coloration, and reduced number of presacral vertebrae) (Sweet 1978, 1984). Based on Sweet's work and genetic studies conducted by Chippindale *et al.* (1990, 1992, 1993b), the Barton Springs salamander was formally described in June 1993 (Chippindale *et al.* 1993a). An adult male (based on external examination only) collected from Barton Springs Pool in November 1992 was selected to be the holotype (Chippindale *et al.* 1993a).

The water that discharges at Barton Springs originates from the Barton Springs segment of the Edwards aquifer (hereafter referred to as the "Barton Springs segment"). Barton Springs is the fourth largest spring in Texas, exceeded only by Comal, San Marcos, and San Felipe springs (Brune 1981). The Barton Springs salamander is found near three of four hydrologically connected spring outlets that collectively make up Barton Springs. These three spring outlets are known as Parthenia (=Main), Eliza (=Concession, =Elk's), and Sunken Garden (=Old Mill, =Walsh) springs, and they occur in Zilker Park, which is owned and operated by the City of Austin. No salamanders have been found at the fourth spring outlet, which is in Barton Creek immediately above Barton Springs Pool (Chippindale *et al.* 1993a,b; Sweet, pers. comm., 1993; Robert Hansen, City of Austin, *in litt.*, 1995a; William Russell, Texas Speleological Survey, *in litt.* 1995). The area around the main spring outlet (Parthenia Springs) was impounded in the late 1920's to create Barton Springs Pool. Flows from Eliza and Sunken Garden springs are also retained by concrete structures, forming small pools located on either side of Barton Springs Pool. The salamander has been observed at depths of about 0.1 to 5 meters (m) (0.3 to 16 feet (ft)) of water under gravel and small rocks, submerged leaves, and algae; among aquatic vegetation; and buried in organic debris. It is generally not found on exposed limestone surfaces or in silted areas (Sweet 1978; Dr. Charles Sexton, City of Austin, *in litt.*, 1992; Chippindale *et al.* 1993a,b; Jim Collett, Robert Hansen, and Mateo Scoggins, City of Austin, pers. comms., 1994–1995; Lisa O'Donnell, U.S. Fish and Wildlife Service (USFWS), pers. obs., 1996).

"Dozens or hundreds" of individuals were estimated to occur among sunken leaves in Eliza Pool during the 1970's (Chippindale *et al.* 1993a,b), while fewer than 15, and occasionally no individuals, were observed during surveys conducted in Eliza Pool between 1987 and 1992 (Chippindale *et al.* 1993a,b). No salamanders were observed at this location between December 1993 and May 1995 (Paul Chippindale, University of Texas at Arlington, Collett, Hansen, and Scoggins; pers. comms., 1994–1995; Hansen *in litt.* 1995b). Numbers ranged from 0 to 28 between June 1995 and July 1996, and dead salamanders have been found (O'Donnell, unpubl. data, 1995–1996).

The Barton Springs salamander was reportedly abundant among the aquatic vegetation in the deep end of Barton Springs Pool when it was collected in 1946 (Hillis and Chippindale 1992; Chippindale *et al.* 1993a,b). Between 1989 and 1991, Sexton (*in litt.*, 1992) reported finding salamanders under rock rubble immediately adjacent to the main spring outflows on "about one out of four [snorkeling] dives." On July 28, 1992, at least 50 salamanders (David Hillis, University of Texas at Austin, pers. comm., 1993) were found over an area of roughly 400 square (sq) m (4 300 sq ft) near the spring outflows in Barton Springs Pool, about 3 to 5 m (10 to 15 ft) below the water (Chippindale *et al.* 1993a,b). Following reports of a fish kill on September 28, 1992, attributed to the improper application of chlorine to clean Barton Springs Pool, only 10 to 11 salamanders were observed and could only be found in an area of about 5 sq m (54 sq ft) in the immediate vicinity of the Parthenia Spring outflows (Chippindale *et al.* 1993a,b). At least 80 individuals were observed during the first comprehensive survey effort conducted in Barton Springs Pool on November 16, 1992, and about 150 individuals were seen on November 24, 1992 (Chippindale *et al.* 1993a,b). A comprehensive survey conducted immediately following an October 1994 flood event reported a total of 16 salamanders, and a total of 10 salamanders was counted in March 1995 (Hansen, *in litt.* 1995c).

The City of Austin initiated monthly transect surveys in June 1993 to provide more consistent data concerning the range and size of the Barton Springs salamander population in Barton Springs Pool. Survey counts ranged from 1 to 27 individuals (mean = 13) between July 1993 and March 1995. The highest survey counts (27 individuals) were reported in November 1993 and May 1994. The lowest counts (ranging from 1 to 6 individuals) occurred during a five-month period following the October 1994 flood event (Hansen, *in litt.* 1995c). Survey counts between April 1995 and April 1996 ranged from 3 to 45 salamanders (City of Austin, unpubl. data).

The salamander was first observed at Sunken Garden Springs on January 12, 1993 (Chippindale *et al.* 1993b). Less than 20 individuals have been reported on any given visit to that outlet (Chippindale 1993b; Hansen, pers. comm., 1995). Because it is part of the Barton Springs complex and is hydrologically connected to Parthenia Springs, biologists had speculated that the salamander occurred at Sunken Garden Springs. However, no salamanders were observed during previous surveys conducted at this location between 1987 and 1992. Low water levels and the presence of large rocks and sediment make searching for salamanders difficult at Sunken Garden Springs (Chippindale *et al.* 1993b; O'Donnell, pers. obs., 1995).

No evidence exists that the species' range extends beyond the immediate vicinity of Barton Springs. Despite survey efforts and searches at other spring outlets, caves, and uncased wells in the Barton Springs segment, no other locations of the Barton Springs salamander have been found (Chippindale *et al.* 1993a,b; Russell, *in litt.* 1995; Russell 1996; Hillis; Andy Price, Texas Parks and Wildlife Department; Sweet; pers. comms., 1993; Hansen, *in litt.* 1995a). No other species of *Eurycea* is known to occur in this portion of the aquifer. Although the extent to which the Barton Springs salamander occurs in the aquifer is unknown, it is likely concentrated near the spring openings where food supplies are abundant, water chemistry and temperatures are relatively constant, and where the salamander has immediate access to both surface and subsurface habitats. Barton Springs is also the main discharge point for the entire Barton Springs segment, and is one of the few perennial springs in the area.

The Barton Springs salamander's diet is believed to consist almost entirely of amphipods (*Hyallela azteca*) and other small invertebrates (James Reddell, Texas Memorial Museum, University of Texas at Austin, pers. comm., 1993; Hillis and Chippindale 1992; Chippindale *et al.* 1993a,b). Primary predators of the Barton Springs salamander are believed to be fish and crayfish (Chippindale *et al.* 1993a,b; Collett, Hansen, and Scoggins, pers. comms., 1995). Observations of larvae and females with eggs indicate breeding occurs year-round (Chippindale, pers. comm., 1993; Collett, Hansen, and Scoggins, pers. comms., 1994–1995). The Barton Springs salamander's eggs are white (Lynn Ables and Streett Coale, Dallas Aquarium; Jim Dwyer, Midwest Science Center; pers. comms., 1996) and have never been observed in the wild (Chippindale, Hillis, and Price, pers. comms. 1993; Collett, Hansen, and Scoggins, pers. comms., 1994–1995; O'Donnell, pers. obs., 1995–1996).

The Barton Springs segment covers roughly 400 sq kilometers (km) (155 sq miles (mi)) from southern Travis County to northern Hays County, Texas, and has a storage capacity of over 37,000 hectare-meters (300,000 acre-feet) (Slade *et al.* 1985, 1986). The watersheds of the six creeks upstream (west) of the recharge zone span about 684 sq km (264 sq mi). This area is referred to as the contributing zone and includes portions of Travis, Hays, and Blanco counties. The recharge and contributing zones (hereafter referred to collectively as the "Barton Springs watershed") make up the total area that provides water to the aquifer, which equals about 917 sq km (354 sq mi). A detailed description of the Barton Springs segment of the Edwards aquifer can be found in the Service's February 17, 1994, proposed rule (59 FR 7968). Porous limestone, karst aquifers, such as the Barton springs segment may transport pollutants rapidly once such materials enter the creeks or other recharge features (EPA 1990, TWC 1989, Slade *et al.*1986, Ford and Williams 1994, Notenboom *et al.* 1994)

Because of the characteristics of karst aquifers, Barton Springs is believed to be heavily influenced by the quality and quantity of runoff, particularly in the recharge zone (City of Austin 1991; Slade *et al.* 1986). Thus, increasing urban development over the area supplying recharge waters to the Barton Springs segment can threaten water quality within the aquifer. The Texas Water Commission (now known as the Texas Natural Resource Conservation Commission (TNRCC)) identified the Edwards aquifer as being one of the most sensitive aquifers in Texas to groundwater pollution (TWC 1989; Hart, *in litt.*, 1991; TNRCC 1994).

Previous Federal Action

The Barton Springs salamander was a Category 2 candidate species on the Service's candidate notices of review from December 30, 1982 (47 FR 58454; September 18, 1985; 50 FR 37958; January 6, 1989; 54 FR 554; and November 21, 1991; 56 FR 58804) until publication of the proposed rule to list the species as endangered (59 FR 7968; February 17, 1994). Dr. Mark Kirkpatrick and Ms. Barbara Mahler petitioned the Service to list the Barton Springs salamander on January 22, 1992, and on December 11, 1992 (57 FR 58779), the Service published a notice in the **Federal Register** that the petition presented substantial information that the requested action may be warranted. A proposed rule to list the Barton Springs salamander was published in the **Federal Register** on February 17, 1994 (59 FR 7968). The Service held a public hearing on June 16, 1994, in Austin, Texas (59 FR 27257). On March 10, 1995, the Service published a notice extending the 1-year deadline for final action on the proposed rule until August 17, 1995, and reopened the public comment period (60 FR 13105).

On April 10, 1995, Congress enacted a moratorium prohibiting work on listing actions (Public Law 104–6) and eliminated funding for the Service to conduct final listing actions. On November 27, 1995, in response to a lawsuit from the Save Our Springs Legal Defense Fund (Save Our Springs Legal Defense Fund, Inc., *et al.* v. Bruce Babbitt), a U.S. District Court invalidated the Service's March 10, 1995, notice of extension and ruled that the Service had to make a final determination on whether or not to list the Barton Springs salamander within 14 days of the court order. The court granted a stay pending the Service's appeal of the order, on the grounds that the moratorium and lack of funding prohibited the Service from making a final listing determination. The moratorium was lifted on April 26, 1996, by means of a Presidential waiver, at which time limited funding for listing actions was made available through the Omnibus Appropriations Act (Pub. L. No. 104–134, 100 Stat. 1321, 1996). The Service published guidance for restarting the listing period on May 16, 1996 (61 FR 24722). Due to the potential for new information during the lapse between the reinstatement of the listing program and the close of the last 45-day comment period (May 17, 1995), the Service reopened the public comment period on June 24, 1996, for 30 days. That comment period closed July 10, 1996, by U.S. District Court order.

On September 4, 1996 (61 FR 46608), the Service withdrew the proposed rule to list the Barton Springs salamander as endangered based on a conservation agreement signed by the Service and the TNRCC, Texas Parks and Wildlife Department (TPWD), and Texas Department of Transportation (TxDOT) on August 13, 1996. The goal of the Barton Springs Salamander Conservation Agreement and Strategy (Agreement) is to continue existing and initiate new management actions to protect the Barton Springs ecosystem and its watershed. The Agreement is administered by the Barton Springs Salamander Conservation Team (BSSCT), which includes representatives from each of the four signatory agencies. In deciding to withdraw the proposed listing rule, the Service found that the Agreement, by protecting water quality at Barton Springs and in the Barton Springs segment of the Edwards aquifer and by conserving water quantity, reduces the threats to the species to the point where listing is no longer warranted.

On March 25, 1997, the U.S. District Court for the Western District of Texas found the Service's withdrawal invalid and ordered the Service to make a listing determination within 30 days. The court ordered the Service to ignore the Agreement in making the new decision. On April 8, 1997, the Service requested the court to delay the due date for the new listing decision until July 23, 1997, so that the Service could reopen the comment period and consider information developed since July 10, 1996, when the comment period on the proposed listing closed. The court denied this request on April 15, 1997. The Service is therefore not able to consider the following information in making a final listing determination: (1) The Agreement and the BSSCT's efforts to implement it, including public and technical input given as part of the BSSCT's March 1, 1997 public workshop; (2) updated salamander survey results; (3) the City of Austin's revised pool maintenance procedures designed to reduce salamander mortality; (4) the discovery of a new salamander location upstream from the Barton Springs Pool; (5) two additional ovipositioning events at the Dallas Aquarium; (6) reinstatement of the Save Our Springs (SOS) ordinance; (7) the Barton Creek Watershed Protection Initiative with private landowners and the Nature Conservancy of Texas; and (8) and adoption of TNRCC's chapters 313 and 216 of the Texas Administrative Code (see discussion under Factor D below).

Summary of Comments and Recommendations

In the February 17, 1994, proposed rule (59 FR 7968) and associated **Federal Register** notices, including notification of a public hearing (59 FR 27257; May 26, 1994) and each of the five comment periods (February 17 to April 18, 1994 (59 FR 7968); May 26 to July 1, 1994 (59 FR 27257; May 26, 1994); July 8 to July 29, 1994 (59 FR 35089; July 8, 1994); March 10 to May 17, 1995 (60 FR 13105; March 10, 1995); and June 24 to July 10, 1996 (61 FR 32413; June 24, 1996)), all interested parties were requested to submit factual reports or information to be considered in making a final listing determination. Appropriate Federal and State agencies, local governments, scientific organizations, and other interested parties were contacted and asked to comment. Legal notices of the public hearing, which invited general public comment were published in the Dripping Springs Century News and Austin-American Statesman on June 8, 1994, in the Drippings Springs Dispatch on June 9, 1994, and in the Austin Chronicle on June 10, 1994. The Service received 657 written and oral comments, 8 videotapes, 5 petitions, and 2 resolutions from individuals and agencies. Of the 657 comments, 524 supported the proposed action, 123 opposed it, and 10 stated neither support nor opposition. Four petitions totaling over 1,800 signatures and one resolution from the City of Austin supported listing, and one petition containing 29 signatures and one resolution from the City of Dripping Springs opposed the listing.

A public hearing was held in two sessions on June 16, 1994, at the Lyndon Baines Johnson Auditorium at the University of Texas at Austin. Over 160 people attended the public hearing, and 74 provided oral testimony.

The Service solicited formal scientific peer review of the proposal from six individuals during the March 10 to May 17, 1995, comment period and received comments from three reviewers. The major comments from these peer reviewers are: the Barton Springs salamander is a distinct species restricted to Barton Springs; the salamander appears to be primarily a surface-dwelling species that retreats underground during unfavorable conditions (such as drought) and to lay eggs; the salamander is vulnerable to declining water quality and quantity and other forms of habitat modification; regulations are inadequate to protect the Barton Springs salamander; the Service should present more data that show increasing levels of pollutants in the groundwater; the Service should provide further explanation as to why the Barton Springs salamander is restricted to Barton Springs; and increased nutrient levels should not affect dissolved oxygen concentrations in the aquifer. The peer reviewers' comments are reflected in this final rule.

Written and oral comments are incorporated into this final rule where appropriate. Comments not incorporated are addressed in the following summary. Comments of a similar nature or point are grouped and summarized. Where differing viewpoints on an issue were expressed, the Service briefly summarizes the general issue.

1. *Comment*: Several commenters questioned whether information regarding threats to the Barton Springs salamander is adequate to support a listing decision. Some commenters stated that threats to the salamander are greater now than ever before.

Service Response: Section 4(a)(1) of the Act states that species shall be listed as threatened or endangered provided that the continued existence of the species is threatened by one or more of the five factors discussed below in the "Summary of Factors Affecting the Species" section of this rule. Under section 4(b)(1), the Service must make its listing decisions based on the best scientific and commercial data available. The Service has met these requirements in this listing decision.

Over 50 percent of the water used by Texans comes from groundwater. The Barton Springs watershed provides the sole source of drinking water for more than 35,000 people living over the aquifer and contributes a significant supply of water to the Colorado River, which is the primary source of drinking water for the City of Austin. In addition to providing a reliable supply of safe drinking water that requires little or no treatment, many people depend on the Barton Springs watershed for other needs, including agriculture and recreational activities.

Amphibians are known to be very sensitive to environmental contaminants (see Factor E below). Because the Barton Springs salamander lives at the main discharge point for the aquifer and is continuously exposed to the waters emanating from it, it is a primary indicator of the health of this natural resource. As an important indicator species, the Barton Springs salamander serves as an early warning sign of deteriorating water quality and quantity in the Barton Springs watershed, which affects the health and well-being of the human population that depends on this resource.

2. *Comment*: The Service received comments questioning the sensitivity of the Barton Springs salamander to changes in water quality and quantity, and asserting that since the salamander has survived past impacts, it appears to be hardy and resilient and able to withstand future impacts.

Service Response: Although the Barton Springs salamander has survived past impacts, only 4 to 6 percent of the Barton Springs watershed is currently developed, and development is expected to continue. Furthermore, although the species as a whole has persisted to date, survey information indicates that individual salamanders have not survived certain impacts, and the species and its prey base are vulnerable to changes in water quality and quantity (see Factors A and E below). As discussed in Factor E, the difficulty in maintaining and propagating the Barton Springs salamander in captivity provides further evidence that this species is sensitive to environmental change. Toxicity data for the salamander's primary food source, *Hyallela azteca*, demonstrate the sensitivity of that amphipod to contaminants.

3. *Comment*: Several people commented on the adequacy of the existing rules and regulations in protecting water quality and quantity in the Barton Springs watershed. One commenter specifically mentioned that, because only two oil pipeline spills have been recorded (see Factor A), regulations are apparently adequate to protect water quality.

Service Response: The Act states that species shall be listed based on one or more of the five factors discussed in this final rule. The Service's analysis of the inadequacy of existing regulatory mechanisms (Factor D) demonstrates that additional measures are needed to protect the Barton Springs salamander from extinction. Although certain rules and regulations provide some water quality and quantity benefits, they do not alleviate all of the identified threats to the Barton Springs salamander.

4. *Comment:* Several inquiries were made regarding possible effects of listing the Barton Springs salamander on land use in the Barton Springs watershed and whether listing would infringe on private property rights. Other comments discussed possible economic impacts and benefits from listing.

Service Response: While economic effects, private property rights, and related concerns, cannot be considered in listing decisions, such factors are considered in recovering listed species. By **Federal Register** notice on July 1, 1994 (59 FR 34272), the Secretaries of Interior and Commerce set forth an interagency policy to minimize social and economic impacts consistent with timely recovery of listed species. Thus, it is the Service's desire that any recovery actions associated with the Barton Springs salamander minimize adverse social and economic impacts to the extent practicable.

5. *Comment:* The Service received several comments on the status of the Barton Springs salamander's population size, stating that this information should be considered in making a listing determination.

Service Response: Data from monthly surveys of the Barton Springs salamander are presented in the Background section and Factor A of this final rule. These survey data further support the need for listing. Although it may be an important listing consideration, the absolute population size does not need to be declining to warrant listing under the Act.

6. *Comment:* The Service received several comments regarding whether the Barton Springs salamander is restricted to Barton Springs.

Service Response: Survey information of other springs, caves, and wells in the Barton Springs segment provided since publication of the proposed rule further substantiate that the Barton Springs salamander's range is limited to the immediate vicinity of Barton Springs (see Background). Because Sunken Garden Springs is part of the Barton Springs complex and scientists assumed that the Barton Springs salamander occurred there, the presence of salamanders at this spring outlet does not indicate that the salamander's range has expanded, as some commenters asserted.

7. *Comment:* Many people questioned whether recreational use of Barton Springs Pool is likely to impact the Barton Springs salamander.

Service Response: The Service recognizes that swimming is a compatible activity with conservation of the salamander. The Service has provided additional discussion on recreation related issues in Factor E ("Other natural or manmade factors affecting its continued existence") of this final rule. The Service acknowledges in both the proposed and final rules that certain pool maintenance practices may impact the Barton Springs salamander, and that the City of Austin is continuing to seek solutions that benefit both the recreational aspect of Barton Springs Pool and the Barton Springs salamander (see Factor A).

8. *Comment:* The Service received several comments regarding whether critical habitat should be designated for the Barton Springs salamander.

Service Response: Critical habitat has not been proposed for the Barton Springs salamander (see Critical Habitat section below). The Act requires that critical habitat be designated for a species at the time it is listed unless designation is not prudent or not determinable. Listing regulations at 50 CFR 424.12(a)(1) provide that critical habitat is not prudent if no benefit to the species is derived from its designation. Designation of critical habitat benefits a listed species only when adverse modification or destruction of critical habitat could occur without the survival and recovery of the species also being jeopardized. Because the Barton Springs salamander is restricted to one area that discharges water from the entire Barton Springs watershed, any action that would result in adverse modification or destruction of the salamander's critical habitat would also jeopardize its continued survival and recovery. Designating critical habitat would therefore not provide a benefit to the species beyond the benefits already provided by listing and subsequent evaluation of activities under the jeopardy standard of section 7 of the Act. Because jeopardy to the species and adverse modification of its critical habitat are indistinguishable, the Service has determined that designation of critical habitat for the Barton Springs salamander is not prudent.

9. *Comment:* A few commenters questioned whether the Barton Springs salamander represents a distinct species.

Service Response: The Barton Springs salamander was first recognized as a distinct species in the 1970's (see Background). A formal description of the salamander was peer-reviewed and published in June 1993 (Chippindale *et al.* 1993a). Although the Barton Springs salamander may bear some morphological resemblance to other *Eurycea* salamander species, differences in its morphology, its isolation from other *Eurycea* populations, and genetic research provide sufficient evidence to support its designation as a distinct species.

10. *Comment:* The Service received comments questioning whether a relationship exists between increasing urbanization and declining water quality and quantity.

Service Response: A discussion of the relationship between increasing urbanization and declining water quality and quantity is presented in Factor A of this final rule.

11. *Comment:* Some commenters questioned whether reduced aquifer levels and encroachment of the bad water line constitute threats to the Barton Springs salamander.

Service Response: A discussion of this issue is presented in Factor A. Under the 1996 pumping and drought regime, springflows at Barton Springs reached historically low levels, and both Eliza Pool and Sunken Garden Springs drained completely dry during drawdown of Barton Springs Pool. Barton Springs is located near the bad water line, and encroachment of bad water to the springs has occurred historically under low flow conditions. During periods of low flows, Sunken Garden Springs measures high levels of total dissolved solids, indicating bad water encroachment.

Factor A also presents information on the increasing number of new permitted wells in the Barton Springs segment and a discussion of groundwater pumpage. A substantial increase in groundwater withdrawals (compounded by drought) will increase the frequency, severity, and/or duration of low aquifer levels and springflows and the potential for movement of the bad water line toward Barton Springs. Increased pumpage may also increase leakage from the lower Trinity aquifer, which contains higher levels of total dissolved solids and fluoride than water in the Barton Springs segment, thus further lowering water quality.

12. *Comment:* The Fish and Wildlife Service needs to implement its new directives from the Department of Interior and Commerce, including scientific peer review, minimization of social and economic impacts, greater predictability, the ecosystem approach, and State agency involvement.

Service Response: The Service has followed its policy directives in preparing this final rule. During the reopening of the public comment period following the notice to extend the final listing decision (60 FR 13105; March 10, 1995), the Service formally solicited peer review from six independent specialists to evaluate the information presented in the proposed rule. The beginning of this section ("Summary of Comments and Recommendations") summarizes the opinions of the three individuals who provided peer review. Informal peer review was also solicited during the public hearing and each public comment period, during which the Service received over 650 letters of comment. The Service solicited information and expertise from Federal, State, and local agencies, including the U.S. Geological Survey, Texas Parks and Wildlife Department, Texas Natural Resource Conservation Commission, Barton Springs/Edwards Aquifer Conservation District, and the City of Austin in preparing the proposed and final rules, and provided written notifications to these agencies of the 90-day finding and proposed rule.

The Available Conservation Measures section of this final rule identifies specific activities that will not be affected by section 9 of the Act regarding "take" of the Barton Springs salamander, and provides guidance and recommendations for avoiding impacts to the salamander. The recovery plan will be drafted to minimize social and economic impacts while ensuring the long-term survival and recovery of the Barton Springs salamander. Protecting the ecosystem upon which the salamander and people depend will be an important component in recovery planning.

13. *Comment:* The Service refuses to acknowledge the benefits of existing regulations. The Service's unwillingness to enforce its own limited and inadequate requirements further contributes to the endangered status of the Barton Springs salamander.

Service Response: As stated in the proposed rule, the Service acknowledges that the existing rules and regulations provide some benefits to water quality and quantity. However, the purpose of Factor D is to evaluate the inadequacies of existing regulatory mechanisms. The Service hopes that this evaluation will assist in identifying measures to strengthen efforts to protect water quality and quantity in the Barton Springs watershed and to promote the long-term survival of the Barton Springs salamander.

14. *Comment:* The Service must consider spill response programs designed to remediate the contamination of groundwater resources by hazardous substance and hazardous waste releases.

Service Response: The Service is unaware of any concerted, organized effort among the various Federal, State, and local agencies to implement a contingency plan for emergency spills in the Barton Springs watershed. Also, efforts to restore contaminated groundwater to its original purity may be technologically infeasible and/or cost-prohibitive (see Factor A). Spill remediation is especially problematic for catastrophic spills that occur in proximity to Barton Springs or in areas that are difficult to access. Because remediation is not always effective or possible, prevention is needed to ensure the protection of water resources.

15. *Comment:* Many of the references cited in the proposed rule are not studies or reports specific to Barton Springs, Austin, or even the Edwards aquifer, but instead describe general nationwide or statewide environmental management issues. These are general policy documents, which do not address the circumstances faced by the Barton Springs salamander.

Service Response: Most of the reports and documents cited in this final rule specifically address the effects of urbanization on surface and groundwater, karst aquifers, the Barton Springs watershed, the Barton Springs salamander, and/or the salamander's primary food source, and thus are pertinent to evaluating threats to the Barton Springs salamander. The information presented in these reports is highly consistent with respect to the threat of urbanization on water resources.

16. *Comment:* The Service cites a 1986 study by Slade *et al.* that projected a doubling of water demands from the year 1982 to 2000. Since we are more than halfway through the 18-year time period, are more recent data available?

Service Response: The estimated total pumpage in 1982 was 470 hectare-meters (3,800 acre-feet), at which time discharge from the Barton Springs segment (withdrawal plus springflow) was determined to be roughly equal to recharge. Slade *et al.* (1986) predicted that a substantial increase in groundwater withdrawal (compounded by drought) would cause a decrease in the quantity of water in the aquifer and discharge from Barton Springs. The Barton Springs/Edwards Aquifer Conservation District estimated total pumpage for 1994 at 570 hectare-meters (4,600 acre-feet). However, as stated in Factor A, the exact volume of water that is pumped from the aquifer is difficult to estimate, since meter reports are not required for non-permitted wells. Furthermore, groundwater pumpage varies considerably from year to year, influenced primarily by the amount of rainfall. The volume of pumpage increases and its effects on aquifer levels and springflows become more pronounced during dry spells, whereas periods of high rainfall can mask the effects of increased dependence on groundwater supplies.

17. *Comment:* There appears to be no direct, quantifiable relationship between water quality in Barton Creek and water quality at Barton Springs.

Service Response: The Background section and Factor A of this final rule discuss the hydrologic regime of the Barton Springs watershed. The surface and groundwaters of the Barton Springs watershed are integrally related, and all of the six creeks that cross the recharge zone of the aquifer affect water quality at Barton Springs. Because of the karst characteristics of the aquifer and because Barton Springs is the main discharge point for the entire watershed, pollutants entering the watershed from any of the recharge sources may eventually reach Barton Springs. The USGS has clearly demonstrated that water quality in Barton Creek has the most immediate impact on water quality at Barton Springs of any recharge source in the Barton Springs watershed because of its recharge contribution and proximity to Barton Springs. Data show that contaminants in Barton Creek can enter the aquifer near Barton Springs and discharge from the springs within hours or days of storm events.

18. *Comment:* The waters from the outlying areas of the contributing zone are not the cause of current degradation and will never significantly contribute to the degradation of the springs compared to the existing development around Barton Springs. Many existing land uses were constructed and operated under less stringent standards. Retrofitting existing development would result in far more improvement of water quality than would further restriction of new development.

Service Response: The Service acknowledges that there is a relationship between current water quality and quantity degradation and existing development and considers retrofitting of these developments to be an important factor in protecting Barton Springs. However, water quality at Barton Springs is also influenced by the quality and quantity of water throughout the entire watershed (see Background and Factor A). Although water quality at Barton Springs responds most rapidly to changes in water quality in Barton Creek, Barton Springs represents a mixture of all of the recharge waters in the Barton Springs watershed. High-quality water in the undeveloped portions of the Barton Springs watershed helps disperse and dilute pollutants from the urbanized areas. Because of the karst characteristics of the aquifer, pollution can originate from anywhere within the Barton Springs watershed, especially pollutants that are relatively stable and mobile in water. Thus, as urbanization expands across the watershed, the ability of the aquifer to dilute and disperse increasing pollutant loads will decrease. While the Service concurs that retrofitting of existing development near Barton Springs may be important to protect water quality, measures are also needed to ensure continued protection of water quality and quantity throughout the remainder of the watershed. A report prepared for the City of Austin (1995) examines options for retrofitting developments to improve stormwater quality in the Barton Springs watershed.

19. *Comment:* The proposed rule did not discuss other sources of water contributing to flows from Barton Springs, including the San Antonio segment of the Edwards aquifer and the Colorado River.

Service Response: Independent studies (Slade et al. 1985, 1986; Stein 1995) conclude that most of the water discharging from Barton Springs originates from within the Barton Springs watershed (see Background section). However, under low flow conditions, the bad water zone of the San Antonio segment appears to flow northward toward Barton Springs. Upward leakage from the lower Trinity aquifer may also infiltrate the Barton Springs segment during low flows. Because these aquifers are high in total dissolved solids, their contribution affects the quality of water in the Barton Springs watershed and at Barton Springs.

The Service is unaware of any reports or data indicating that the Colorado River contributes water to the Barton Springs watershed. However, Barton Springs does supply baseflow to the Colorado River, which may be substantial during dry periods.

20. *Comment:* The Service must comply with the National Environmental Policy Act (NEPA) prior to listing the Barton Springs salamander as endangered. This would require the Service to study the social and environmental impacts of the proposed listing and prepare appropriate environmental documentation.

Service Response: The Service has determined that Environmental Assessments and Environmental Impact Statements, as defined under the authority of the National Environmental Policy Act of 1969, need not be prepared in connection with regulations adopted pursuant to section 4(a) of the Endangered Species Act of 1973, as amended. A notice outlining the Service's reasons for this determination was published in the **Federal Register** on October 25, 1983 (48 FR 49244).

21. *Comment:* The statement that "Loop 360 provides a major route for transportation of petroleum and gasoline products to service stations in the Austin area" is unsupported by any data or citation of a study. What is the basis of this statement?

Service Response: This statement was based on the fact that no designated hazardous materials routes exist for the Austin area, and thus all major roadways can be considered to be transportation routes for hazardous materials. Because Loop 360 supports a high volume of traffic, and many service stations exist in this part of the Austin area, it is considered to be a major transportation route. The Service's statement is also supported by the Hazardous Materials Water Contamination Risk study prepared for the City of Austin (1994).

22. *Comment:* Both Hays County and Dripping Springs experienced high rates of growth in the 1980's, yet are still sparsely populated. The Service's statement in the proposed rule suggests these areas will soon be overrun with people at intensely urbanized levels, which is an unrealistic assumption.

Service Response: The Service quoted a study (see Factor A) conducted by the Capital Area Planning Council. Additional information on population growth for the northern portion of Hays County is presented in this final rule.

23. *Comment:* More of the recharge and contributing zones have been developed than the Service states in the proposed rule. Based on an analysis of historical trends in land development for the recharge zone of the Barton Springs segment, approximately 1,200 hectares (ha) (3,050 acres (ac)) in the recharge zone had been developed in 1979. Approximately 3,000 ha (7,500 ac) had been developed by 1993, which represents approximately 13 percent of the entire recharge zone of the Barton Springs segment.

Service Response: Factor A of the proposed rule states that "* * * only about 3 to 4 percent of the recharge and contributing zones is currently developed," which was based on an estimate of impervious cover provided by the USGS. A report prepared for the City of Austin (1995) has estimated impervious cover over the Barton Springs watershed to be 6 percent (see Factor A). Assuming that the commenter's calculations of development are also equal to the amount of impervious cover, the commenter's assertion that about 13 percent of the recharge zone is developed does not appear to be inconsistent with the estimated 3 to 6 percent impervious cover for the entire watershed.

24. *Comment:* What evidence exists that demonstrates that sediments entering the pools where the salamander occurs actually settle in the salamander's habitat?

Service Response: Biologists with the City of Austin have found that silt and sediments that are hosed from the shallow end into the deep end of Barton Springs Pool during cleaning reduce the amount of available salamander habitat. Increased sediment influxes following major rain events also reduce habitat availability. Sediments cover much of the bottom of Eliza Pool and Sunken Garden Springs, and the Barton Springs salamander is typically found in silt-free areas near the spring outlets.

25. *Comment:* A significant number of references cited in the proposed rule are not peer-reviewed scientific publications and thus should not be given the same level of credibility as those having a more rigorous review and approval process.

Service Response: All official agency reports cited in the proposed rule have undergone extensive internal review, and some have [illegible] outside peer review. Articles cited from scientific journals have all received formal peer review. Although the Service relies primarily on final documents in making listing decisions, the best available information may also come from other sources such as written correspondence, factual information and data from draft documents, expert opinions, and personal communications. The Service strives to evaluate the accuracy of this "gray literature" before considering it in making a listing decision.

26. *Comment:* Several individuals commented on the methods and results of certain reports used by the Service in the proposed rule, including three USGS reports (Slade *et al.* 1985, 1986; Veenhuis and Slade 1990) and a Barton Springs/Edwards Aquifer Conservation District (BS/EACD) report (Hauwert and Vickers 1994). The Service was also criticized for not making available for public review and comment the raw data upon which these and other reports cited by the Service are based.

Service Response: The reports cited in the proposed rule and in this final rule present sufficient information and data needed to review and assess the methodologies used by the investigators, their study results and data analyses, and conclusions. The Service has reviewed these reports and determined that the data were gathered and analyzed in accordance with sound scientific principles, and accepts these reports as valid and relevant scientific information. Furthermore, the results and conclusions of independent studies consistently show similar trends regarding impacts of urbanization on water quality and quantity. The USGS and BS/EACD have both provided written responses to the criticisms of their reports (Raymond Slade, USGS, *in litt.* 1994; Nico Hauwert, BS/EACD *in litt.* 1995; Bill Couch, BS/EACD, *in litt.* 1996).

27. *Comment:* The occurrence of turbidity, accumulation of sediments, and contaminants in Barton Springs watershed could be due to natural phenomena.

Service Response: The volume of sediments observed in urbanizing portions of the Barton Springs watershed and increased turbidity during periods of major construction indicate that such activities influence these phenomena. As discussed in Factor A, the relationship between urban runoff and increased erosion and sedimentation is well documented. Increases in turbidity tend to coincide with land clearing and construction activities, and discharge of turbid runoff from construction projects has been observed entering receiving waters in the Barton Springs watershed.

Research shows that the contaminants discussed in Factor A (including elevated levels of nutrients, heavy metals, petroleum hydrocarbons, and pesticides) are primarily associated with urban runoff. The Service is unaware of any natural sources in the Barton Springs watershed that could result in significant concentrations (or any detectable concentrations for manmade compounds such as pesticides) of these contaminants in water.

28. *Comment:* A report by T.U. Taylor (*in litt.* 1922) states that elevated levels of fecal coliform bacteria have been documented at Barton Springs since 1922. However, the Service stated in the proposed rule that the City of Austin determined that the method used to measure bacterial counts at the time of the report is different from that used today, and thus "the bacterial counts are not directly comparable to * * * current sampling techniques" (Austin Librach, City of Austin, *in litt.*, 1991). The City of Austin's review of the report does not provide a basis for refuting its conclusions or excluding them from further consideration. The comparison of fecal coliform counts taken in the context of the standards of the time, to counts taken today and in the context of today's standards, is a valid comparison.

Service Response: To date, the Service has only been provided a copy of a cover letter (dated August 28, 1922) to a supplementary report submitted by Mr. Taylor to the City of Austin. The letter states the need to filter Barton Springs water for human consumption due to contamination with "B. coli." Because no report accompanied the letter, and the Service has been unable to obtain a copy of the report, the Service can draw no further conclusions regarding its findings.

29. *Comment:* What is the basis for the Service's statement that "contaminants that adsorb to the surface of sediments may be transported through the aquifer and later be released back into the water column"?

Service Response: The Service based this statement on information presented in Schueler (1987), which states that once deposited, pollutants in "enriched sediments can be remobilized under suitable environmental conditions posing a risk to benthic life" (see Factor A).

30. *Comment:* The Service received a comment letter that contained a document comparing the findings and conclusions of the proposed rule with those made in a report by the Aquatic Biological Advisory Team (ABAT), which concluded that insufficient information appears to exist to support a listing decision.

Service Response: The City of Austin and Texas Parks and Wildlife Department formed the ABAT, which consisted of five nationally recognized specialists, to make research and management recommendations needed to conserve the Barton Springs and Bull Creek watersheds and their resident salamander populations (the Barton Springs and Jollyville Plateau salamanders). The ABAT members were specifically instructed not to make recommendations regarding listing nor to evaluate specific laws or regulations. The Service believes that substantial evidence exists to support a listing determination for the Barton Springs salamander, but also recognizes that additional research is important to assist in making sound management recommendations. The Service concurs with most of the ABAT's management recommendations, which could be incorporated into a regional management plan for the Barton Springs watershed, as well as a recovery plan for the Barton Springs salamander.

31. *Comment:* The TNRCC and TxDOT provided information regarding existing and proposed rules and regulations, which they state are adequate to protect the Barton Springs salamander.

Service Response: An evaluation of the existing rules and regulations is provided in Factor D of this final rule. The Service encourages State and local entities to identify proposed regulations and additional protective measures that can serve as a basis for a regional management plan for the Barton Springs watershed.

Summary of Factors Affecting the Species

After thorough review and consideration of all information available, the Service has determined that the Barton Springs salamander should be classified as an endangered species. Procedures found at section 4 of the Act and regulations implementing the listing provisions of the Act (50 CFR part 424) were followed. A species may be determined to be endangered or threatened due to one or more of the five factors described in section 4(a)(1). These factors and their application to the Barton Springs salamander (*Eurycea sosorum* Chippendale, Price, and Hillis) are as follows:

A. *The present or threatened destruction, modification, or curtailment of its habitat or range.* The primary threat to the Barton Springs salamander is degradation of the quality and quantity of water that feeds Barton Springs resulting from urban expansion over the Barton Springs watershed (including roadway, residential, commercial, and industrial development). A discussion of some potential effects of contaminants on the salamander and its prey base (amphipods) is provided in this section and under Factor E. Potential factors contributing to declining water quality and quantity in this portion of the Edwards aquifer include chronic degradation, catastrophic hazardous material spills and increased water withdrawals from the aquifer. Also of concern are impacts to the salamander's surface habitat.

Urbanization can dramatically alter the normal hydrologic regime and water quality of an area. As areas are cleared of natural vegetation and topsoil and replaced with impervious cover (paved surfaces), rainfall no longer percolates through the ground but instead is rapidly converted to surface runoff. Creekflow shifts from predominantly baseflow, which is derived from natural filtration processes and discharges from local groundwater supplies, to predominantly stormwater runoff. The amount of stormwater runoff tends to increase in direct proportion to the amount of impervious cover. With increasing stormflows, the amount of baseflow available to sustain water supplies during drought cycles is diminished and the frequency and severity of flooding increases. The increased amount and velocity of runoff increases erosion and streambank destabilization, which in turn leads to increased sediment loadings, channel widening, and changes in the morphology and aquatic ecology of the affected creek (Schueler 1991). Sediment from soil erosion is "by volume the greatest single pollutant of surface waters and is the potential carrier of most pollutants found in water" (Menzer and Nelson 1980).

Urbanization introduces many pollutants into an area, including suspended solids, nutrients, petroleum hydrocarbons, bacteria, heavy metals, volatile organic compounds, fertilizers, and pesticides (TWC 1989; EPA 1990; Schueler 1991; Notenboom *et al.* 1994; Menzer and Nelson 1980). Stormwater runoff is a primary source of water pollution. Pollutant loadings in receiving waters, particularly in areas that have little or no pollution controls, generally increase with increasing impervious cover (Schueler 1991). A report by the USGS on the relationship between urbanization and water quality in streams throughout the Austin area (9 of 18 sample sites were along streams in the Barton Springs segment and its contributing zone) demonstrated statistically significant increases in constituent concentrations with increasing impervious cover (Veenhuis and Slade 1990). Degradation of water quality in the Barton Springs watershed is also evidenced by algal blooms, erosion, trash and debris, and accumulations of sediments and toxics (City of Austin 1995).

Water quality in the aquifer and at Barton Springs is directly affected by the quality of water in the six creeks that cross the recharge zone (see Background section). Of these creeks, water quality at Barton Springs responds most rapidly to changes in water quality in Barton Creek (Slade *et al.* 1986; City of Austin 1991). Data show that contaminants in Barton Creek can enter the aquifer near Barton Springs and discharge from the springs within hours or days of storm events (Slade *et al.* 1986; City of Austin 1991). Because groundwater originating from Barton Creek remains in the aquifer for short periods before discharging at the springs, there is little time for attenuation of pollutants before discharging at Barton Springs (Slade *et al.* 1986; City of Austin 1991). Increases in turbidity (a measure of suspended solids or sediment), algal growth, nutrients, and fecal-group bacteria have been documented along Barton Creek between SH 71 and Loop 360 and at Barton Springs, and have been largely attributed to construction activities and the conveyance and treatment of sewage in this area (Slade *et al.* 1986; Austin Librach, City of Austin *in litt.*, 1990; City of Austin 1991, 1993; Barbara Britton, TWC, *in litt.*, 1992).

Water quality in the more heavily developed areas of the Barton Springs segment and at Barton Springs is also beginning to show signs of degradation (Slade *et al.* 1986; Librach *in litt.*, 1990; City of Austin 1991, 1993; Slade 1992; Hauwert and Vickers 1994; Texas Groundwater Protection Committee (TGPC) 1995). The BS/EACD found elevated levels of sediment, fecal-group bacteria, trace metals, nutrients, and petroleum hydrocarbons in certain springs and wells between Sunset Valley and Barton Springs (Hauwert and Vickers 1994, TGPC 1994). Slade *et al.* (1986) reported that levels of fecal-group bacteria, nitrate nitrogen, and turbidity were highest in wells near creeks draining developed areas. In addition to sediments and bacteria, tetrachloroethene, a commonly used drycleaning solvent, has been detected in water samples from Barton Springs (Slade 1991). Possible sources of groundwater contamination include urban runoff, construction activities, leaking septic tanks and pipelines, and petroleum storage tank releases (Slade *et al.* 1986; TWC 1989; EPA 1990; Hauwert and Vickers 1994).

One of the most immediate threats to the Barton Springs salamander is siltation of its habitat, owing primarily to construction activities in the Barton Creek watershed (Slade *et al.* 1986, City of Austin 1991, Hauwert and Vickers 1994, TGPC 1994). Major highway, subdivision, and other construction projects along Barton Creek increased during the early 1980's and 1990's. While high turbidity has been observed in Barton Springs Pool following major storm events since the early 1980's (Slade *et al.* 1986; Hauwert 1995), the duration and frequency of sediment discharges from Barton Springs increased substantially during the 1990's (Hauwert 1995; TGPC 1994). Barton Springs discharged large amounts of sediments following most major rain events in 1993, 1994 (Hauwert and Vickers 1994; TGPC 1994), and 1995 (Collett, pers. comms., 1994–1995). Sediments have been observed emanating directly from the spring outlets in Barton Springs Pool (Doyle Mosier, Lower Colorado River Authority; Debbie Dorsey, City of Austin; pers. comms., 1993; Collett and Hansen, pers. comms., 1994–1995) about 8 to 12 hours following the start of a heavy rain (Slade *et al.* 1986; City of Austin 1991; Hauwert and Vickers 1994; David Johns, City of Austin, pers. comm. 1996).

Several uncased wells in the Barton Creek watershed, one of which is located 5 km (3 mi) south of Barton Springs near the Loop 360 bridge, have been completely filled with a cream-colored, carbonate silt (up to 45 m (150 ft)) (Hauwert and Vickers 1994). A well in Sunset Valley measured 1 to 1.5 ft accumulations of cream-colored sediment over an eight-month period prior to July 1993, and reportedly caused the well pump to seize (Hauwert and Vickers 1994). Several well owners, drillers, and operators also reported a significant influx of sediments during 1993, particularly during periods of heavy rainfall and low water-level conditions (Hauwert and Vickers 1994).

Studies have shown that high levels of suspended solids reduce the diversity and density of aquatic fauna (EPA 1986; Barrett *et al.* 1995). In Barton Springs Pool, the lowest recorded population counts of the salamander (ranging from 1 to 6 individuals) occurred over the five-month period following an October 1994 flood event (see Background section). The flood deposited a large amount of silt and debris over the salamander's habitat in the pool, and the area occupied by the salamander during the following months was reduced to the silt-free areas immediately adjacent to the spring outlets (Hansen, *in litt.*, 1995c).

In addition to covering the salamander's habitat, problems resulting from increased sediment loads may include: Clogging of the gills of aquatic species, causing asphyxiation (Garton 1977; Werner 1983; Schueler 1987); smothering their eggs and reducing the availability of spawning sites (EPA 1986; Schueler 1987); filling interstitial spaces and voids, thereby reducing water circulation and oxygen availability (EPA 1986); filling and blocking of recharge features and underground conduits, restricting recharge and groundwater storage volume and movement; reducing light transmission needed for photosynthesis, food production, and the capture of prey by sight-feeding predators (EPA 1986; Schueler 1987); and exposing aquatic life to contaminants that readily bind to sediments (such as petroleum hydrocarbons and heavy metals). Once deposited, pollutants in "enriched sediments can be remobilized under suitable environmental conditions, posing a risk to benthic life" (Schueler 1987).

Research indicates that species in or near contaminated sediments may be adversely affected even if water-quality criteria are not exceeded (Landrum and Robbins 1990; Medine and McCutcheon 1989). Sediments act as a sink for many organic and inorganic contaminants (Menzer and Nelson 1980; Landrum and Robbins 1990; Medine and McCutcheon 1989) and can accumulate these contaminants to levels that may impact aquatic ecosystems (Landrum and Robbins 1990; Medine and McCutcheon 1989). Metal-contaminated sediment toxicity studies have shown *Hyallela azteca*, the primary food item of the Barton Springs salamander, to be the most sensitive organism of those tested (Phipps *et al.* 1995; Burton and Ingersoll 1994). Most polycyclic aromatic hydrocarbons (PAHs), a component of oil, are associated with sediments in aquatic ecosystems, which may be ingested by benthic organisms (Eisler 1987). *Hyallela azteca* has been shown to assimilate PAHs from contaminated sediments (Eisler 1987). Sediments collected from the main stem of Barton Creek on November 21, 1994, about 150 m above Barton Springs Pool, contained several PAHs that were 2.5 to 22 times the levels shown to always have a toxic effect (survival, growth, or maturation) on *Hyallela azteca* (City of Austin, unpubl. data, 1994; Ingersoll *et al.*, in press). Sediments collected from Barton Springs on April 20, 1995, also contained PAHs at levels up to 6.5 times those shown to be toxic to *Hyallela azteca* (City of Austin, unpubl. data, 1995; Ingersoll *et al.*, in press).

In addition to sediment concentrations, high levels of total petroleum hydrocarbons have been detected in water samples from Sunken Garden Springs (Hauwert and Vickers 1994). Petroleum hydrocarbons include both aliphatic hydrocarbons and PAHs (Albers 1995). Normal concentrations of petroleum hydrocarbons in the Edwards aquifer are below the detection limit of 1.0 mg/l. However, levels of total petroleum hydrocarbons measured 1.9 mg/l following a 9-mm (0.35-in) rain event in March 1994, and 1.3 mg/l in April 1994. A well that is hydrologically connected with Barton Springs contained a level of 2.1 mg/l in May 1993 (Hauwert and Vickers 1994; BS/EACD 1994). Petroleum hydrocarbons may enter water supplies through sewage effluents, urban and highway runoff, and chronic leakage or acute spills of petroleum and petroleum products (Eisler 1987; Hauwert and Vickers 1994; Albers 1995).

Water samples from Sunken Garden Springs also contained elevated levels of lead, which are commonly found in petroleum-contaminated waters. Total and dissolved lead levels at Sunken Garden Springs measured 0.024 and 0.015 mg/l, respectively (Hauwert and Vickers 1994; BS/EACD 1994). Typical freshwater concentrations for lead are between 0.001 and 0.01 mg/l (Menzer and Nelson 1980). The EPA drinking water standard for total lead is 0.015 mg/l. In aquatic environments, dissolved lead is the most toxic form, and adverse effects (including reduced survival, impaired reproduction, and reduced growth) on aquatic biota have been reported at concentrations of 0.001 to 0.005 mg/l (Eisler 1988a). Sources of lead in water may include industrial discharges, highway runoff, and sewage effluent (Pain 1995).

Aquatic organisms may absorb lead through skin, gills, intestines, and other organs, and may ingest lead through feeding (Pain 1995). Lead concentrations tend to be highest in benthic organisms, which may assimilate lead directly from sediments (Eisler 1988a). Research indicates that lead is not essential or beneficial to living organisms, and that all known effects are deleterious, including those on survival, growth, reproduction, development, behavior, learning, and metabolism (Eisler 1988a; Pain 1995). Adverse effects increase with elevated water temperatures, reduced pH, younger life stages, and long exposures (Eisler 1988a; Pain 1995). Synergistic and additive effects may also occur when lead is mixed with other metals or toxic chemicals (Eisler 1988a). Studies have shown that lead is highest in urban streams and lowest in rural streams, and that species diversity is also greater in rural streams than urban ones (Eisler 1988a).

Arsenic, which has been used in the manufacture of agricultural pesticides and other products (Eisler 1988b) and may be found in roadway and urban runoff, has been detected in wells in the Barton Springs watershed at levels exceeding EPA drinking water standards (0.05 mg/l) (Hauwert and Vickers 1994) and in other areas of Texas (TWC 1989). Concentrations of arsenic compounds adversely affecting aquatic biota have been reported at 0.019 to 0.048 mg/l (Eisler 1988b). Toxicity of arsenic to aquatic life depends on many factors, including water temperature, pH, suspended solids, organic content, phosphate concentration, presence of other contaminants, arsenic speciation, and duration of exposure. As with many contaminants, early life stages are most sensitive, and large differences in responses exist between species (Eisler 1988b).

Leaking underground storage tanks "are considered to be one of the principal contributing sources of ground-water pollution, placing a significant loading on the State's aquifers, due to their regional distribution and high number which are estimated to be leaking" (TWC 1989). Chronic releases from leaking tanks represent a serious risk of water contamination (City of Austin 1994). The TNRCC (1994) lists leaking underground storage tanks as one of the top three most frequently encountered sources of groundwater contamination in the Edwards aquifer. Common pollutants from leaking underground storage tanks include gasoline, diesel, and other oil products (TWC 1989). The TNRCC's "Leaking Petroleum Storage Tank Case Report" lists 626 leaking petroleum storage tanks for Hays and Travis counties for the period between October 1984 and April 1995, of which 158 cases resulted in some form of groundwater contamination. Fifteen of the reports specifically identified impacts to the Edwards aquifer, of which only three had been officially closed or were near closure.

The conveyance and treatment of sewage in the watershed, particularly in the recharge zone, may also impair water quality. Sewage effluent may contain organics (including PAHs), metals, nutrients (nitrogen and phosphorus), inorganic acids, and microorganisms (Eisler 1987; Menzer and Nelson 1980; TWC 1989; City of Austin 1991, 1993; Notenboom *et al.* 1994). Sewage contamination has occurred at Barton Springs following major rain events (TWC 1989), and high bacterial counts and algal blooms have been reported (Slade *et al.* 1986; City of Austin 1991). In 1982, high levels of fecal coliform bacteria at Barton Springs were attributed to a sewerline leak upstream from Barton Springs Pool. While fecal coliform bacteria are believed to be harmless, they indicate the presence of other organisms that may be pathogenic to aquatic life (Lager *et al.* 1977), some of which may pose a threat to salamanders and/or their prey base.

Wastewater discharges have been identified as a primary cause of algal blooms, which have been a recurring problem in both Barton Creek and at Barton Springs (City of Austin 1991, 1993). Increased nutrients promote eutrophication of aquatic ecosystems, including the growth of bacteria, algae, and nuisance aquatic plants, and lowered oxygen levels. Menzer and Nelson (1980) note that "changes in nutrient pools must eventually directly affect the productivity of the entire ecosystem, even though the effects may not be measurable in biologic terms until a number of years later." Because most nutrients in urban runoff are present in soluble form and are thus readily consumed by algae, nutrient concentrations present in urban runoff tend to stimulate algal blooms (Schueler 1987). A 5 km-(3-mi) long algal bloom observed along Barton Creek in April 1993 may have been the result of an accidental discharge of 1.6 million liters (440,000 gallons) of effluent and irrigation water from a golf course (City of Austin 1993, 1995).

Based on USGS data (Slade *et al.* 1986), the average level of nitrates at Barton Springs Pool has increased from about 1.0 mg/l (measured as nitrate nitrogen) prior to 1955 to a 1986 level of about 1.5 mg/l. Sunken Garden Springs measured greater than 2.0 mg/l nitrate nitrogen during the BS/EACD study (Hauwert and Vickers 1994). Elevated nitrate concentrations in groundwater are attributed primarily to human activities (TWC 1989). Total nitrogen (as nitrogen) concentrations measured in wells in the more urbanized areas of the Barton Springs watershed are typically two to six times higher than in rural areas (Slade 1992). Elevated levels of total phosphorus and orthophosphorus have also been detected in certain springs and wells in the Barton Springs watershed (Slade 1992; Hauwert and Vickers 1994). In addition to wastewater discharge, other possible sources of nutrients in the Barton Springs watershed include fertilizers, solid wastes, animal waste, and decomposition of natural vegetation (Hauwert and Vickers 1994; Slade *et al.* 1986).

Over 145 km (90 mi) of wastewater lines occur in the recharge zone of the Barton Springs segment (Maureen McReynolds, City of Austin Water and Wastewater Utility, pers. comm., 1993). Most of the creeks contributing recharge to the Barton Springs segment are underlain by wastewater lines, and five wastewater treatment plants are located within the Barton Springs watershed (City of Austin 1991). Leaking septic tanks and inadequate filtering in septic fields have also been identified as a major source of groundwater contamination, particularly for older systems (TWC 1989; EPA 1990; City of Austin 1991; Hauwert and Vickers 1994; TNRCC 1994). The TNRCC (1994) cites septic tanks as the most frequently encountered source of groundwater contamination in the Edwards aquifer. Although the amount of effluent leached from an individual septic system may be small, the cumulative impact over the landscape can be significant, especially for karst aquifers (EPA 1990). An estimated 4,800 septic systems currently exist in the Barton Springs watershed and may contribute as much as 23 percent of the total nitrogen load to the aquifer (City of Austin 1995).

Highways can have major impacts on groundwater quality (TNRCC 1994; Barrett *et al.* 1995). The TNRCC (1994) lists highways and roads as the fifth most common potential source of groundwater contamination in the Edwards aquifer. Elevated concentrations of metals, Kjeldahl nitrogen, and organic compounds have been detected in groundwater near highways and their control structures. Highway construction can also cause large increases in suspended solids to receiving waters (Barrett *et al.* 1995). Several major highways have been built over the recharge zone since the late 1980's, and the expansion of US 290 from SH 71 through Oak Hill to a six-lane freeway is underway. US 290 crosses the Barton Creek watershed and discharges stormwater runoff from detention ponds into tributaries of Barton Creek. Bypass events from a regional water quality pond at the US 290/Loop 360 interchange have resulted in significant sediment deposition along the entire length of an unnamed tributary and a portion of Barton Creek (City of Austin, *in litt.* 1995; City of Austin, unpubl. data, 1996; USFWS, *in litt.* 1996), less than 5 km (3 mi) from Barton Springs.

Organophosphorus pesticides commonly used in urban areas tend to degrade rapidly in the environment, but certain pesticides may remain biologically active for some time (Eisler 1986, Hill 1995). For example, diazinon, which is commonly used in commercial and residential areas, may remain biologically active in soils for up to 6 months under conditions of low temperature, low moisture, high alkalinity, and lack of microbial degraders (Eisler 1986). Diazinon has shown adverse effects on stream insects at concentrations of 0.3 micrograms/l (Eisler 1986). To ensure protection of sensitive aquatic fauna, Eisler (1986) recommends that levels of diazinon in water not exceed 0.08 micrograms/l. Many organophosphorus compounds may result in adverse effects after short-term exposures. Exposure may include contact with or ingestion of contaminated water, sediments, or food items (Hill 1995).

Increasing urbanization also increases the risk of catastrophic spills. Because of the Barton Springs salamander's limited range, a single catastrophic spill has the potential to impact the entire species and its habitat. Catastrophic spills can result from major transportation accidents, underground storage tank leaks, pipeline ruptures, sewage spills, vandalism, and other sources. Because no designated route for hazardous materials exists for the Austin area, potentially hazardous materials may be transported on major roadways crossing the Barton Springs watershed (City of Austin 1994). Expansion of major roadways and increasing volumes of traffic, particularly across the recharge zone near Barton Springs, increases the threat of catastrophic spills.

Oil pipeline ruptures also represent a source of groundwater contamination with potentially catastrophic consequences. Three oil pipelines run roughly parallel to each other across the Barton Springs watershed and cross Barton Creek near the Hays/Travis county line. Two of these lines have ruptured within the recharge zone about 13 km (8 mi) south of Barton Springs, which constitute the largest spills reported from Hays and Travis counties between 1986 and 1992 (TWC, unpubl. data). The first major spill occurred in 1986, about 270 m (300 yards) from Slaughter Creek, when an oil pipeline was severed during a construction operation and released about 366,000 liters (96,600 gallons) of oil. Although about 91 percent of the spill was reportedly recovered (Rose 1986), petroleum hydrocarbon fumes were detected about six weeks later in caves located up to 2.7 km (1.7 mi) northeast of the spill (Russell 1987). The second pipeline break occurred in 1987 near the first spill site and released over 190,000 liters (49,000 gallons) of oil. According to the TWC database, more than 97 percent of this spill was recovered (TWC, unpubl. data).

Response times to hazardous materials spills vary, depending on several factors including detection capability, location and size of the spill, weather conditions, whether or not the spill is reported, and the party performing the cleanup. In some cases, spills may go undetected and/or unreported. Generally, cleanup is initiated within several hours once the spill has been detected and reported, but many weeks or possibly years may be necessary to complete the cleanup effort. In areas where access is difficult (due to remoteness, steep terrain, or other factors), remediation may not be possible or may be ineffective due to delays in initiating cleanup.

Increased demands on water supplies from the aquifer can also reduce the quality and quantity of water in the Barton Springs segment and at Barton Springs. The volume of springflow is regulated by the level of water in the aquifer. Discharge decreases as water storage in the aquifer drops, which historically has resulted primarily from a lack of recharging rains rather than groundwater withdrawal for public consumption. During these low flow conditions, "bad water" within the San Antonio segment of the Edwards aquifer may move northward and contribute to flows from Barton Springs (Slade *et al.* 1986; Stein 1995). In addition, increased withdrawals could result in upward leakage from the underlying Trinity aquifer, which has higher levels of dissolved solids and fluoride than water in the Barton Springs segment (Slade *et al.* 1986).

Under low flow conditions, Barton Springs and a well near the bad water line (YD–58–50–216) have shown increased dissolved solids concentrations, particularly sodium and chloride, indicating encroachment of bad water (Slade *et al.* 1986). The BS/EACD (Hauwert and Vickers 1994) measured high levels of dissolved solids at Sunken Garden Springs, indicating a significant influence of bad water during low flow conditions. The potential for encroachment of the bad water line and/or recharge from the Trinity aquifer increases with pumpage of the aquifer and extended low recharge or low flow conditions (Slade *et al.* 1986). The encroachment of bad water could have negative impacts on the plants and animals associated with Barton Springs. High sodium and chloride levels have been shown to increase fish mortality by disturbing ion balances (Werner 1983).

Based on water-budget analyses and pumpage estimates for 1982 (Slade *et al.* 1985, 1986), discharge from the Barton Springs segment (withdrawal plus springflow) was determined to be roughly equal to recharge from surface waters. Thus, a substantial increase in groundwater withdrawal would be expected to cause a decrease in the quantity of water in the aquifer and discharge from Barton Springs. The estimated total pumpage in 1982 was 470 hectare-meters (3,800 acre-feet), or about 10 percent of the long-term mean discharge of 1,400 l/s (50 cfs) for Barton Springs (Slade *et al.* 1985, 1986). The BS/EACD estimated total pumpage for 1994 to be about 570 hectare-meters (4,600 acre-feet) (Botto and Rauschuber 1995). The exact volume of water that is pumped from the aquifer is difficult to estimate, since meter reports are only required for municipal, industrial, irrigation, and commercial wells and not for wells that pump less than 38,000 l (10,000 ga) per day, domestic wells, or agricultural wells used for non-commercial livestock and poultry operations (BS/EACD 1994). Groundwater pumpage increases considerably and its effects on aquifer levels and springflows become more pronounced during dry spells (Slade *et al.* 1986; D.G. Rauschuber & Associates and R.J. Brandes Co. 1990; BS/EACD 1994; Nico Hauwert and Ron Fiesler, BS/EACD, pers. comms., 1995).

The number of wells in the Barton Springs segment is growing with the increasing dependence on the Edwards aquifer for drinking water, irrigation, and industrial use (BS/EACD 1994 and 1995; Botto and Rauschuber 1995). In the 235 sq mi area of the Barton Springs segment, a total of 54 new wells were drilled between fiscal year (FY) 1989 (September 1, 1988 to August 31, 1989) and FY 1993, with a maximum of 18 wells drilled during a single year (BS/EACD 1995). During FY 1994, 46 new wells were drilled, which is more than two and a half times the number drilled in FY 1993 (BS/EACD 1994). An additional 45 wells were drilled in FY 1995 (BS/EACD 1995). As urbanization in the outlying areas of Austin expands and reliance on groundwater supplies increases, the number of wells and the total volume of water withdrawal is also expected to continue to increase.

In addition to contributing to declining groundwater supplies, the TWC (1989) cites water wells as a major source of groundwater contamination by providing direct access of pollutants into the aquifer and possibly through inter-aquifer transfer of bad water. Reduced groundwater levels exacerbate the problem through decreased dilution of pollutants.

Under the 1996 pumping and drought regime, flows from Barton Springs approached historically low conditions. Because the flows from Eliza and Sunken Garden springs are considerably less than flows from the main springs in Barton Springs Pool (see Background section), the impacts of increased groundwater withdrawals and drought are realized more quickly for these spring outlets. As of July 1996, the water level in both Eliza Pool and Sunken Garden Springs was less than a foot deep (O'Donnell, pers. obs., 1996). Both springs ceased flowing during the drawdown of Barton Springs Pool (Hansen, pers. comm., 1996; O'Donnell, pers. obs. 1996).

Other potential impacts to the salamander's surface habitat may include the use of high pressure fire hoses in areas where the salamander occurs, hosing silt from the shallow end of Barton Springs Pool into the salamander's habitat, diverting water from Sunken Garden Springs into Barton Creek below Barton Springs, and runoff from the train station above Eliza Pool. Following the 1992 fish kill (see Background section), chlorine is no longer used to clean Barton Springs Pool. The City of Austin has drafted a management plan to avoid, minimize, and mitigate impacts to the salamander from pool cleaning and other park maintenance practices.

Impervious cover over the Barton Springs watershed is currently estimated at 4 to 6 percent (Slade 1992; City of Austin 1995). This area is under increasing pressure from urbanization (Austin Transportation Study (ATS) 1994). The ATS has projected that the Austin metropolitan area will support a population of over 1.3 million by the year 2020, up from 815,000 in 1994. Southwest Austin, which covers only a portion of the Barton Springs watershed, is projected to almost double in size, from an estimated 32,000 people in 1994 to 58,000 by the year 2020. Likewise, the population in northern Hays County is expected to more than triple in size by the year 2020, from 18,000 in 1994 to 68,000 in 2020 (ATS 1994). According to the Capital Area Planning Council (CAPCO), Hays County has the second highest growth rate in the ten-county CAPCO region. Dripping Springs, which is located in the contributing zone between Onion Creek and Barton Creek, "will likely continue to experience a high rate of growth as development continues along U.S. 290 from the Oak Hill area westward" (CAPCO 1990).

Several major highways, including a segment of State Highway 45, the southern extension of Loop 1 ("MOPAC"), and the Southwest Parkway have been built in the last decade to accommodate the projected population growth, real estate speculation, and traffic demands in this area. Justification for the Highway 290 expansion was largely based on the population growth projected for and already occurring in this area (ATS 1994). In addition to these roadways, the remainder of State Highway 45, an 82-mi loop around Austin, is proposed to be built within the next 20 to 25 years. This highway would cross Barton Creek and several other creeks in the Barton Springs watershed (City of Austin 1994).

Less than 2,400 ha (6,000 ac) of preserve lands currently exist in the Barton Springs watershed (USFWS 1996). Much of the remaining area along Barton Creek and within the City of Austin's Extra-territorial Jurisdiction (ETJ) is slated for development at levels of greater than 30 percent impervious cover (City of Austin unpubl. data).

B. *Overutilization for commercial, recreational, scientific, or educational purposes.* No threat from overutilization of this species is known at this time.

C. *Disease or predation.* No diseases or parasites of the Barton Springs salamander have been reported. Primary predators of the Barton Springs salamander are believed to be predatory fish and crayfish; however, no information exists to indicate that predation poses a major threat to this species.

D. *The inadequacy of existing regulatory mechanisms.* No existing rules or regulations specifically require protection of the Barton Springs salamander or the Barton Springs ecosystem, and no comprehensive plan is in place to protect the Barton Springs watershed from increasing threats to water quality and quantity. The salamander is not included on the TPWD's list of threatened and endangered species, so the species is not protected by that agency.

Since the publication of the proposed rule, the City of Austin's "Save Our Springs" (SOS) ordinance was overturned by a Hays County jury in November 1994 (*Jerry J. Quick, et al.* v. *City of Austin*). Prior to its invalidation, the SOS ordinance was the most stringent water quality protection regulation in the Barton Springs watershed, requiring impervious cover limitations of 15 to 25 percent (based on net site area), buffers along major creeks, no increases in loadings of 13 pollutants, barring of exemptions and variances from the ordinance provisions, and attempts to reduce the risk of accidental contamination (Camille Barnett, City of Austin, *in litt.*, 1993).

In addition to the overturning of the SOS ordinance, several bills passed during the State's 74th (1995) legislative session that curtail the City of Austin's ability to implement water quality protective measures within its five-mile ETJ. Senate Bill 1017 and House Bill 3193 exempt large developments (over 1,000 acres, or 500 acres if approved by the TNRCC) from all City of Austin water quality ordinances and land use regulations. The TNRCC has determined that this legislation conflicts with State and Federal regulations; does not address groundwater quality; is inadequate to ensure protection of surface water quality and would not meet State water quality standards; provides little or no inspection, enforcement, or compliance safeguards; and would allow surface and groundwater quality to degrade (Mark Jordan, TNRCC, *in litt.*, 1995). Other laws passed during the 1995 session that limit the enforcement authority of local governments include Senate Bill 14, which allows landowners to sue local and State governments to invalidate regulations or seek compensation for actions that would decrease property values by 25 percent or more; and Senate Bill 1704, which "grandfathers" developers from updated health and safety ordinances.

Other laws and regulations potentially affecting water quality in the Barton Springs watershed include the Federal Clean Water Act, Safe Drinking Water Act, Resource Conservation and Recovery Act, and Comprehensive Environmental Response, Compensation, and Liability Act; the Edwards Rules and Texas Underground Storage Tanks Act (30 Texas Administrative Code, Chapters 313 and 334), which are promulgated and enforced by the TNRCC; the City of Austin's water quality protective ordinances (Williamson Creek Ordinance (1980), Barton Creek Watershed Ordinance (1981), Lower Watersheds Ordinance (1981), Comprehensive Watersheds Ordinance (1986), "Composite Ordinance" (1991), and the amended Composite Ordinance (1994); and the City of Dripping Springs' Site Development Ordinance 52B. In addition to the inadequacies of these rules and regulations (discussed below), many of the agencies charged with their administration lack adequate resources to carry out their responsibilities (TNRCC 1994).

The purpose of the Clean Water Act is "to restore and maintain the physical, chemical, and biological integrity of the Nation's waters." Section 304 of the Clean Water Act provides the EPA authority to develop water quality criteria to protect water resources, including groundwater. However, the primary focus of the Clean Water Act is on surface water, and the law does not mandate protection of groundwater resources. Furthermore, surface and groundwater tend to be treated as separate and distinct resources rather than interactively, and protection focuses on human use rather than effects on aquatic organisms. Section 302, which provides for a National Pollution Discharge Elimination System (NPDES), primarily addresses point source pollution and not non-point source pollution or groundwater contamination. Efforts are needed to integrate the relationship between surface and groundwater into the regulatory framework and to assess the impact of surface water regulations and management practices on groundwater resources.

Part C of the Safe Drinking Water Act, the Underground Injection Control Program, requires that the injection of fluids underground not endanger drinking water supplies. Section 1427 (Sole Source Aquifer Program) requires that federally funded projects potentially affecting a sole source aquifer ensure that drinking water will not be contaminated. A portion of the Barton Springs watershed has been designated as a Sole Source Aquifer. The Sole Source Aquifer Program applies only to Federal projects and not to State or private projects, unless they receive Federal funds, and no requirements related to aquatic organisms are included.

The Federal Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response, Compensation, and Liability Act focus on remedial actions once groundwater contamination has occurred, rather than on prevention. Under these Acts, monitoring is required to determine when remediative cleanup actions following groundwater contamination by chemical and waste sites is complete. In addition, the RCRA requires that all underground storage tanks installed since 1988 be equipped with spill and overfill protection devices, protected from corrosion that could result in releases, and equipped with devices that would detect any releases that might occur. Previously existing tanks are to be upgraded to these same standards over a ten-year period.

Much of the responsibility for protecting surface and groundwaters is directed to and administered by the states. Section 106 of the Clean Water Act provides funds to the states for water quality programs, including comprehensive groundwater protection programs. Section 303 requires states to set water quality standards for surface waters, employing the criteria established by the EPA under section 304, and to designate uses for each water body. Section 319 provides technical and financial assistance to the states to implement programs to control nonpoint source pollution for both surface water and groundwater. The EPA's policy, "Protecting the Nation's Groundwater: EPA's Strategy for the 1990's" also recognizes states as having the primary role of protecting groundwater. Section 1428 of the Safe Drinking Water Act, the Wellhead Protection Program, directs states to control sources of contaminants near public supply wells used for drinking water. Most of the State of Texas' efforts to protect surface and groundwater resources focus on point sources of pollution, monitoring, and remediative actions (TNRCC 1994). The TNRCC's Tier II Antidegradation Policy applies only to regulatory actions that would exceed fishable/swimmable quality of Barton and Onion creeks, and allows degradation if necessary for important economic or social development.

The Edwards Rules regulate construction-related activities on the recharge zone of the Edwards aquifer that may "alter or disturb the topographic, geologic, or existing recharge characteristics of a site" as well as any other activity "which may pose a potential for contaminating the Edwards aquifer," including sewage collection systems and hazardous materials storage tanks. The Edwards Rules regulate construction activities though review of Water Pollution Abatement Plans (WPAPs). The WPAPs do not require site-specific water quality performance standards for developments over the recharge zone nor do they address land use, impervious cover limitations, nonpoint source pollution, application of fertilizers and pesticides, or retrofitting for developments existing prior to the implementation of the Rules. (Travis County was incorporated into the Rules in March 1990; Hays County was incorporated in 1984.) The WPAPs also do not apply to development activities in the aquifer's contributing zone. To date, the Edwards Rules do not include a comprehensive plan to address the effects of cumulative impacts on water quality in the aquifer or its contributing zone.

The Edwards Rules and the Texas Underground Storage Tanks Act (Title 31, Chapters 313 and 334 of the Texas Administrative Code) require that all tanks installed after September 29, 1989, be equipped with release detection devices, corrosion protection, and spill/overflow protection; that all previously existing tanks be upgraded to the same standards by December 22, 1994; and that tanks located in the Edwards aquifer recharge and transition zones be of double-walled or equivalent construction with continuous monitoring of the space between the tank and piping walls for leak detection. The adequacy of these measures in preventing groundwater contamination, particularly over the long term, has not been demonstrated. Routine testing of tanks to ensure proper functioning is not required until after a leak has been detected, and no routine monitoring or testing by the TNRCC is conducted to determine compliance with the regulations. Formal approval by the TNRCC of construction plans for new tanks is only required for the recharge zone and not the contributing zone. The TNRCC does not maintain a database of the total number of storage tanks that have been upgraded, those that still need to be upgraded, or those that are in violation of the regulations (Jackie Hardee, TNRCC, pers. comm., 1995).

A Section 10(a)(1)(B) permit allowing the incidental taking of two endangered songbirds and six endangered karst invertebrates, known as the Balcones Canyonlands Conservation Plan (BCCP), was issued to Travis County and the City of Austin in May 1996 (USFWS 1996). The BCCP does not allow incidental taking of the Barton Springs salamander, and requires that all permit applicants ensure that their activities do not degrade waters in the Barton Springs watershed. The guidance provided in the Available Conservation Measures section of this final rule is intended to assist landowners in achieving this goal. Acquisition of 4,000 acres in the Barton Creek watershed as BCCP preserve land will provide additional benefits to the salamander by preserving the natural integrity of the landscape and positively contributing to water quality and quantity in Barton Creek and Barton Springs. The BCCP does not apply to development activities in Hays County.

To protect water quantity in the Barton Springs segment, the BS/EACD has developed a Drought Contingency Plan (D.G. Rauschuber & Associates and R.J. Brandes Co. 1990). Barton Springs has always flowed during recorded history, and one of the BS/EACD's goals is to assure that Barton Springs flow "does not fall appreciably below historic low levels" (D.G. Rauschuber & Associates and R.J. Brandes Co. 1990). The BS/EACD regulates about 60 to 80 percent of the total volume that is pumped from the Barton Springs segment and has the ability to limit development of new wells, impose water conservation measures, and curtail pumpage from these wells during drought conditions (Bill Couch, BS/EACD, pers. comm., 1992, and *in litt.* 1994; Botto and Rauschuber 1995). According to the BS/EACD (B. Couch, pers. comm., 1992), water well production in the higher elevations of the Barton Springs segment has been limited during periods of lower aquifer levels in recent years. However, the ability of the BS/EACD to ensure the success of the plan is limited, since it does not regulate 20 to 40 percent of the total volume that is pumped from the Barton Springs segment.

E. *Other natural or manmade factors affecting its continued existence.* The very restricted range of the Barton Springs salamander makes this species especially vulnerable to acute and/or chronic groundwater contamination. Since the salamander is fully aquatic, there is no possibility for escape from contamination or other threats to its habitat. A single incident (such as a contaminant spill) has the potential to eliminate the entire species and/or its prey base. Crustaceans, particularly amphipods, on which the salamander feeds are especially sensitive to water pollution (Mayer and Ellersieck 1986; Phipps *et al.* 1995; Burton and Ingersoll 1994).

Research indicates that amphibians, particularly their eggs and larvae, are sensitive to many pollutants, such as heavy metals; certain insecticides, particularly cyclodienes (endosulfan, endrin, toxaphene, and dieldrin), and certain organophosphates (parathion, malathion); nitrite; salts; and petroleum hydrocarbons (Harfenist *et al.* 1989). Christine Bishop (Canadian Wildlife Service) states that "the health of amphibians can suffer from exposure to pesticides (Harfenist *et al.* 1989). Because of their semipermeable skin, the development of their eggs and larvae in water, and their position in the food web, amphibians can be exposed to waterborne and airborne pollutants in their breeding and foraging habitats * * *. [Furthermore] pesticides probably change the quality and quantity of amphibian food and habitat (Bishop and Pettit 1992)." Toxic effects to amphibians from pollutants may be either lethal or sublethal, including morphological and developmental aberrations, lowered reproduction and survival, and changes in behavior and certain biochemical processes.

Observations of central Texas *Eurycea* salamanders in captivity indicate that these species, including the Barton Springs salamander, are very sensitive to changes in water quality and are "quite delicate and difficult to keep alive" (Sweet, *in litt.*, 1993). Sweet reported that captive individuals exhibit adverse reactions to plastic containers, aged tapwater, and detergent residues. The water in which these salamanders are kept also requires frequent changing (Sweet, *in litt.*, 1993). Unsuccessful attempts at captive propagation of the San Marcos salamander (Janet Nelson, Southwest Texas State University, pers. comm., 1992) and very limited success at inducing captive spawning in the Barton Springs salamander (Ables, Coale, and Dwyer, pers. comms., 1996) may also be due to these species' sensitivity to environmental stress.

Several citizens have expressed concern over impacts to the salamander from recreational use of Barton Springs Pool for swimming. However, no evidence exists to indicate that swimming in Barton Springs Pool poses a threat to the salamander population, which is located 3 to 5 m (10 to 15 ft) below the water's surface. The survey data show no correlation between recreational use of the pool and salamander abundance. Furthermore, salamander population declines have occurred in Eliza Pool, which is closed to the public. Although certain pool maintenance practices may impact individual salamanders occurring in the pools, they are unlikely to have a major impact on the entire species.

The Service has carefully assessed the best scientific and commercial information available regarding the past, present, and future threats faced by this species in determining to make this rule final. The best scientific data indicate that listing the Barton Springs salamander as endangered is warranted. Critical habitat is determined to be not prudent for this species for the reasons discussed below.

Critical Habitat

Critical habitat is defined in section 3 of the Act as: (i) The specific areas within the geographical area occupied by a species, at the time it is listed in accordance with the Act, on which are found those physical or biological features (I) essential to the conservation of the species and (II) that may require special management considerations or protection; and (ii) specific areas outside the geographical area occupied by a species at the time it is listed, upon a determination that such areas are essential for the conservation of the species. "Conservation" means the use of all methods and procedures needed to bring the species to the point at which protection under the Act is no longer necessary.

Section 4(a)(3) of the Act, as amended, and implementing regulations (50 CFR 424.12) require that, to the maximum extent prudent and determinable, the Secretary designate critical habitat at the time the species is determined to be endangered or threatened. Service regulations (50 CFR 424.12(a)(1)) state that designation of critical habitat is not prudent when one or both of the following situations exist—(1) The species is threatened by taking or other human activity, and identification of critical habitat can be expected to increase the degree of such threat to the species, or (2) such designation of critical habitat would not be beneficial to the species. The Service finds that designation of the springs occupied by the Barton Springs salamander as critical habitat would not be prudent because it would not provide a conservation benefit to the species.

Designation of critical habitat benefits a listed species only when adverse modification or destruction of critical habitat could occur without the survival and recovery of the species also being jeopardized. Because the Barton Springs salamander is restricted to one area that discharges water from the entire Barton Springs watershed, any action that would result in adverse modification or destruction of the salamander's critical habitat would also jeopardize its continued survival and recovery. Designating critical habitat would therefore not provide a benefit to the species beyond the benefits already provided by listing and subsequent evaluation of activities under the jeopardy standard of section 7 of the Act. Because jeopardy to the species and adverse modification of its critical habitat are indistinguishable, the Service has determined that designation of critical habitat for the Barton Springs salamander is not prudent.

Available Conservation Measures

Conservation measures provided to species listed as endangered or threatened under the Act include recognition, recovery actions, requirements for Federal protection, and prohibitions against certain practices. Recognition through listing encourages and results in public awareness and conservation actions by Federal, State, and local agencies, private organizations, and individuals. The Act provides for possible land acquisition and cooperation with the States and requires that recovery actions be carried out for all listed species. The protection required of Federal agencies and the prohibitions against taking and harm are discussed, in part, below.

The health of the aquifer and Barton Springs, and the long-term survival of the Barton Springs salamander, can only be ensured through a concerted, organized effort on the part of all affected Federal, State, and local governments and the private citizenry to protect the Barton Springs watershed. Conservation and management of the Barton Springs salamander will entail removing threats to its survival, including—(1) protecting the quality and quantity of springflow from Barton Springs by implementing comprehensive management programs to control and reduce point and nonpoint sources of pollution throughout the Barton Springs watershed; (2) minimizing the risk and likelihood of pollution events that would affect water quality; (3) strengthening efforts to protect groundwater and springflow quantity; (4) continuing to examine and implement pool cleaning practices and other park operations that protect and perpetuate the salamander's surface habitat and population; and (5) public outreach and education. It is also anticipated that listing will encourage continued research on the critical aspects of the Barton Springs salamander's biology (e.g., longevity, natality, sources of mortality, feeding and breeding ecology, and sensitivity to contaminants and other water quality constituents).

Section 7(a) of the Act, as amended, requires Federal agencies to evaluate their actions with respect to any species that is proposed or listed as endangered or threatened and with respect to its critical habitat, if any is designated. Regulations implementing this interagency cooperation provision of the Act are codified at 50 CFR Part 402. Section 7(a)(1) requires Federal agencies to use their authorities to further the purposes of the Act by carrying out programs for listed species. Section 7(a)(2) requires Federal agencies to ensure that activities they authorize, fund, or carry out are not likely to jeopardize the continued existence of a listed species. If a Federal action may affect a listed species, the responsible Federal agency must enter into consultation with the Service, unless the Service agrees with the agency that the action is not likely to adversely affect the species.

The Act and its implementing regulations set forth a series of general prohibitions and exceptions that apply to all endangered wildlife. These prohibitions, codified at 50 CFR 17.21, in part, make it illegal for any person subject to the jurisdiction of the United States to take (includes harass, harm, pursue, hunt, shoot, wound, kill, trap, or collect, or to attempt any of these), import or export, ship in interstate commerce in the course of commercial activity, or sell or offer for sale in interstate or foreign commerce any listed species. It also is illegal to possess, sell, deliver, carry, transport, or ship any such wildlife that has been taken illegally. Certain exceptions apply to agents of the Service and State conservation agencies. The Barton Springs salamander is not known to be commercially traded and such permit requests are not expected.

Permits may be issued to carry out otherwise prohibited activities involving endangered wildlife species under certain circumstances. Regulations governing permits are at 50 CFR 17.22 and 17.23. Such permits are available for scientific purposes, to enhance the propagation or survival of the species, and/or for incidental take in connection with otherwise lawful activities.

It is the policy of the Service (59 FR 34272; July 1, 1994) to identify to the maximum extent practicable at the time a species is listed, those activities that would or would not constitute a violation of section 9 of the Act. The intent of this policy is to increase public awareness of the effect of listing on proposed and ongoing activities within a species' range, and to assist the public in identifying measures needed to protect the species. Aside from the potential for catastrophic spills, no single development activity or water withdrawal in and of itself is likely to significantly impact water quality and quantity in the Barton Springs watershed. Rather, it is the sum of all of these activities and their associated impacts that threaten this resource and the survival of the Barton Springs salamander. Because most of the threats to the salamander come from diffuse sources that are cumulative in nature, their effects will be observable at the ecosystem and population level rather than at the individual level. Thus, the purpose of this guidance is not only to identify activities that would or would not likely result in "take" of individuals, but activities that in combination will ultimately affect the long-term survival of the Barton Springs salamander. This guidance should not be used to substitute for local efforts to develop and implement comprehensive management programs for the Barton Springs watershed.

Activities that the Service believes are unlikely to result in a violation of section 9 for the Barton Springs salamander are:

(1) Range management and other agricultural practices that promote good vegetative cover and soil conditions (for example, low to moderate stocking rates, rotational and deferred grazing, and maintaining native bunchgrasses);

(2) Swimming in Barton Springs pool;

(3) Buying or selling of property;

(4) Improvements to existing structures, such as renovations, additions, repairs, or replacement;

(5) New developments or construction that do not result in an appreciable change in the quality or quantity of water in the Barton Springs watershed above normal background conditions (non-degradation). Generally, new developments and construction designed and implemented pursuant to State and local water quality protection regulations in effect as of the date of this rule will not result in a violation of section 9;

(6) Routine residential lawn maintenance; and

(7) Upgrading or replacing existing structures (such as bridge crossings, BMPs, septic systems, underground storage tanks) in order to minimize pollutant loadings into receiving waters.

Activities that the Service believes could potentially harm the Barton Springs salamander and result in a violation of section 9 include:

(1) Collecting or handling of the species without appropriate permits;

(2) Alteration or disturbance of the Barton Springs salamander's habitat in the pools where it occurs (including use of chemicals to clean the pools where the salamander occurs; use of high pressure fire hoses in salamander habitat; removal of beneficial aquatic plants; dredging; and frequent and/or prolonged drawdown, particularly during drought);

(3) Illegal discharges or dumping of chemicals, silt, sewage, fertilizers, pesticides, heavy metals, oil, organic wastes, or other pollutants into the Barton Springs watershed;

(4) New developments or construction not designed and/or implemented pursuant to State and local water quality protection regulations in effect as of the date of this rule, that result in an appreciable change in the quality or quantity of water in the Barton Springs watershed above normal background conditions (non-degradation);

(5) Withdrawal of water from the aquifer to the point at which springflows at Barton Springs appreciably diminish;

(6) Withdrawal of water from the contributing zone to the point at which baseflows in the creeks appreciably diminish;

(7) Introduction of non-native aquatic species (fish, plants, other) into Barton Springs or the Barton Springs segment of the Edwards aquifer;

(8) Destruction or alteration of caves, sinkholes, or other significant recharge features (including dumping, vandalism, and/or diverting contaminated water into these features); and

(9) Destruction or alteration of spring orifices that provide water to Barton Springs.

Questions as to whether specific activities will constitute a violation of section 9 should be directed to the Service's Austin Ecological Services Field Office (see **ADDRESSES** section). Requests for copies of the regulations regarding listed wildlife and inquiries regarding prohibitions and permits should be addressed to the U.S. Fish and Wildlife Service, Branch of Endangered Species/Permits, P.O. Box 1306, Albuquerque, New Mexico 87103 (telephone: 505/248–6920; facsimile: 505/248–6922).

National Environmental Policy Act

The Fish and Wildlife Service has determined that Environmental Assessments and Environmental Impact Statements, as defined under the authority of the National Environmental Policy Act of 1969, need not be prepared in connection with regulations adopted pursuant to section 4(a) of the Endangered Species Act of 1973, as amended. A notice outlining the Service's reasons for this determination was published in the **Federal Register** on October 25, 1983 (48 FR 49244).

Required Determinations

The Service has examined this regulation under the Paperwork Reduction Act of 1995 and found it to contain no information collection requirements.

References Cited

A complete list of all references cited in this rule is available upon request from the Austin Ecological Services Field Office (see **ADDRESSES** section).

Author: The primary author of this final rule is Lisa O'Donnell, Austin Ecological Services Field Office (see **ADDRESSES** section).

List of Subjects in 50 CFR Part 17

Endangered and threatened species, Exports, Imports, Reporting and recordkeeping requirements, and Transportation.

Regulation Promulgation

Accordingly, part 17, subchapter B of chapter I, title 50 of the Code of Federal Regulations, is amended as set forth below:

PART 17—[AMENDED]

1. The authority citation for part 17 continues to read as follows:

Authority: 16 U.S.C. 1361–1407; 16 U.S.C. 1531–1544; 16 U.S.C. 4201–4245; Pub. L. 99–625, 100 Stat. 3500, unless otherwise noted.

2. Section 17.11(h) is amended by adding the following, in alphabetical order under AMPHIBIANS, to the List of Endangered and Threatened Wildlife, to read as follows:

§ 17.11 Endangered and threatened wildlife.

* * * * *

(h) * * *

Species		Historic range	Vertebrate population where endangered or threatened	Status	When listed	Critical habitat	Special rules
Common name	Scientific name						
*	*	*	*	*	*	*	
AMPHIBIANS							
*	*	*	*	*	*	*	
Salamander, Barton Springs	*Eurycea sosorum*	U.S.A. (TX)	Entire	E	612	NA	NA
*	*	*	*	*	*	*	

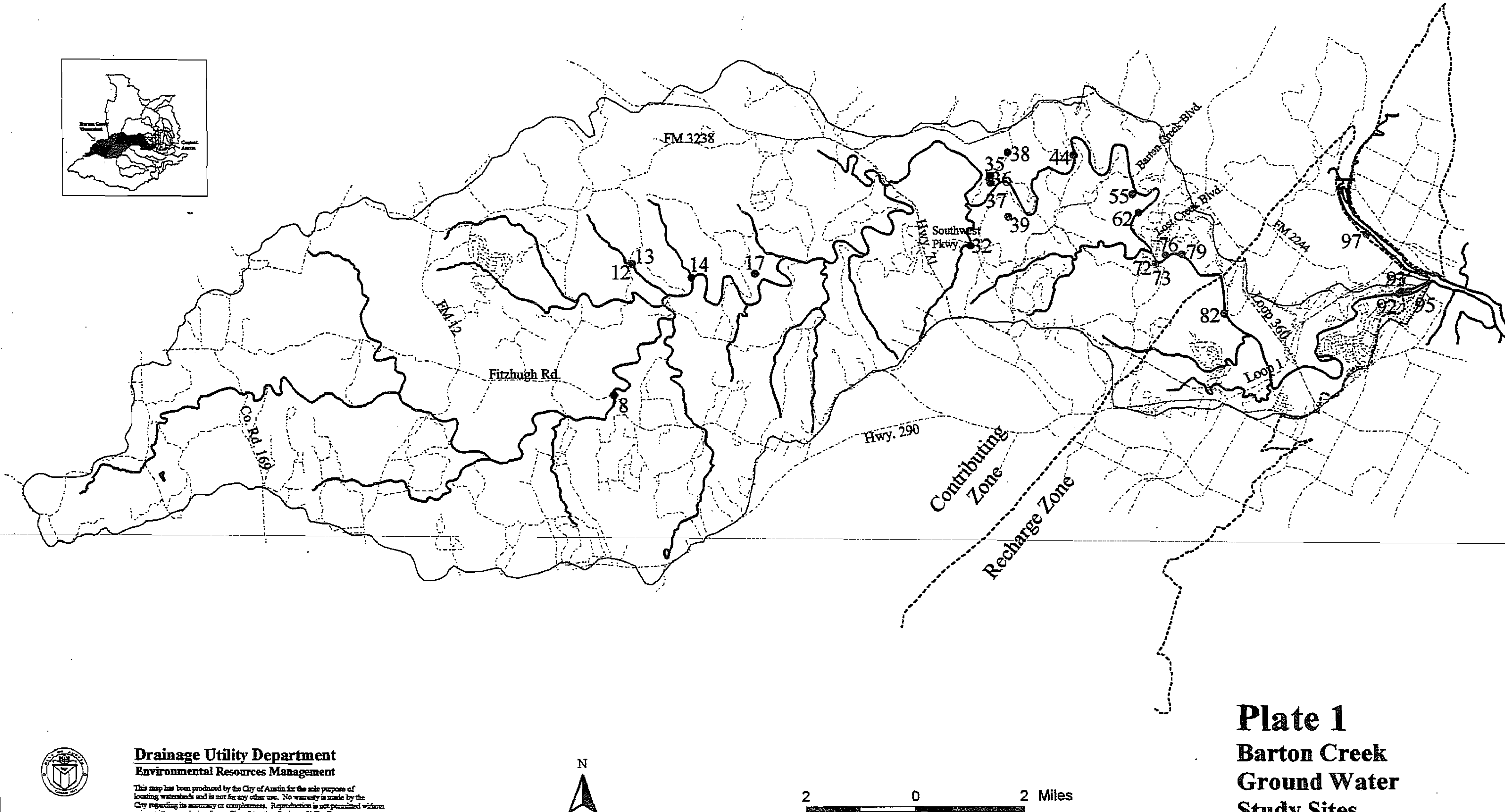
Dated: April 24, 1997.

John G. Rogers,

Acting Director, Fish and Wildlife Service.

[FR Doc. 97–11194 Filed 4–29–97; 8:45 am]

BILLING CODE 4310–55–P



Drainage Utility Department
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Plate 1
Barton Creek Ground Water Study Sites

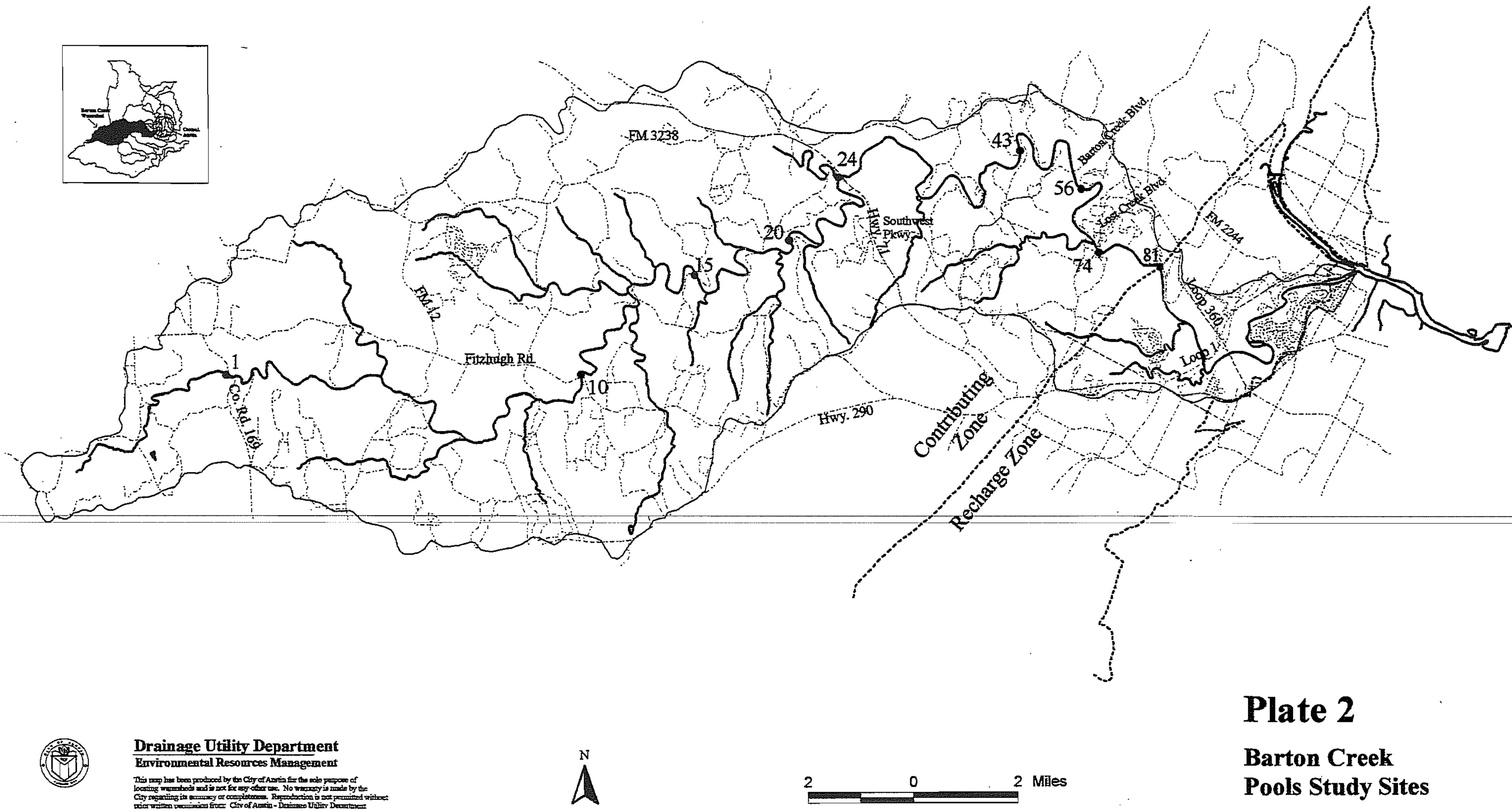

Plate 2

Barton Creek Pools Study Sites

Drainage Utility Department

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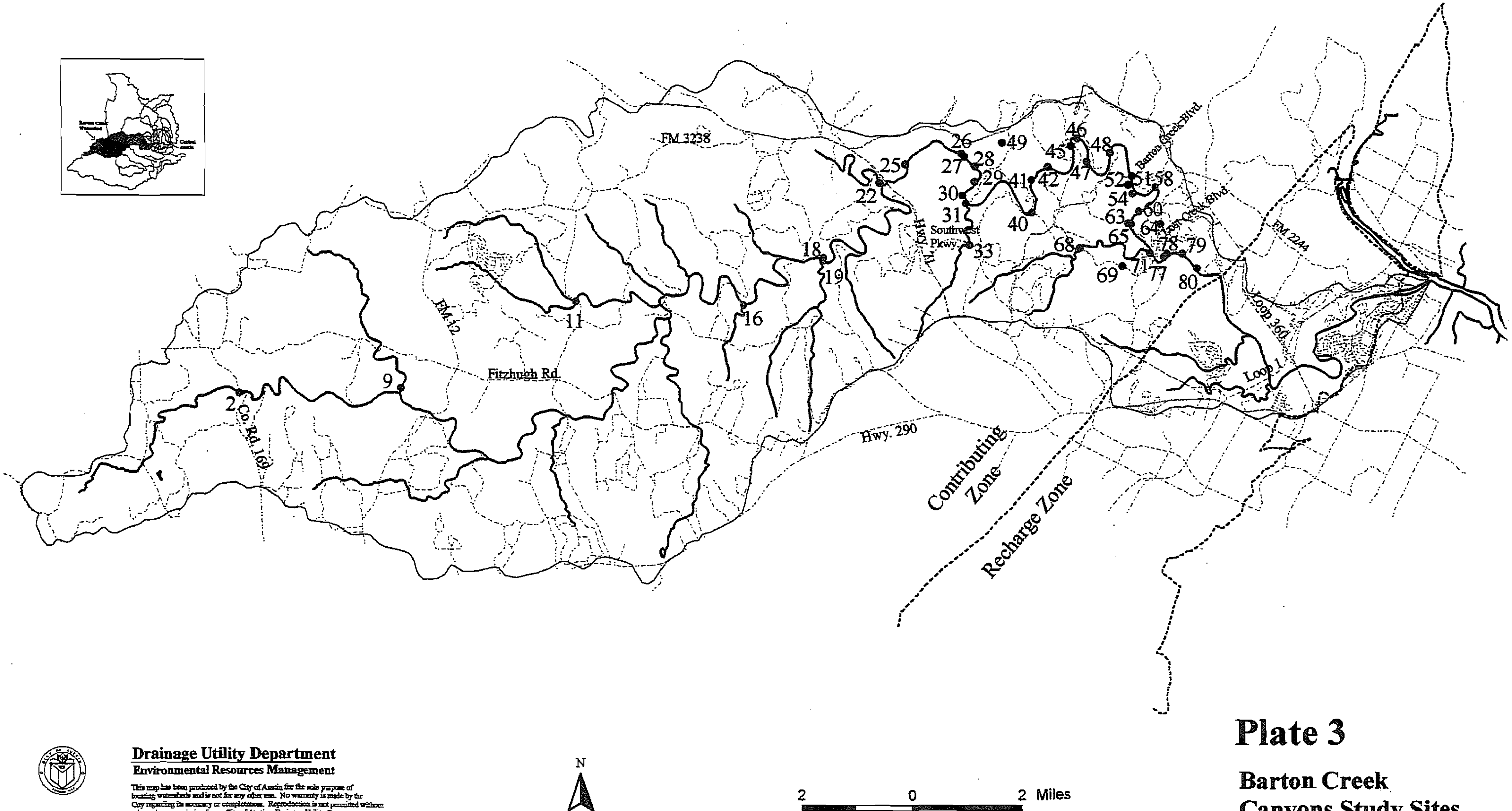

Plate 3

Barton Creek Canyons Study Sites

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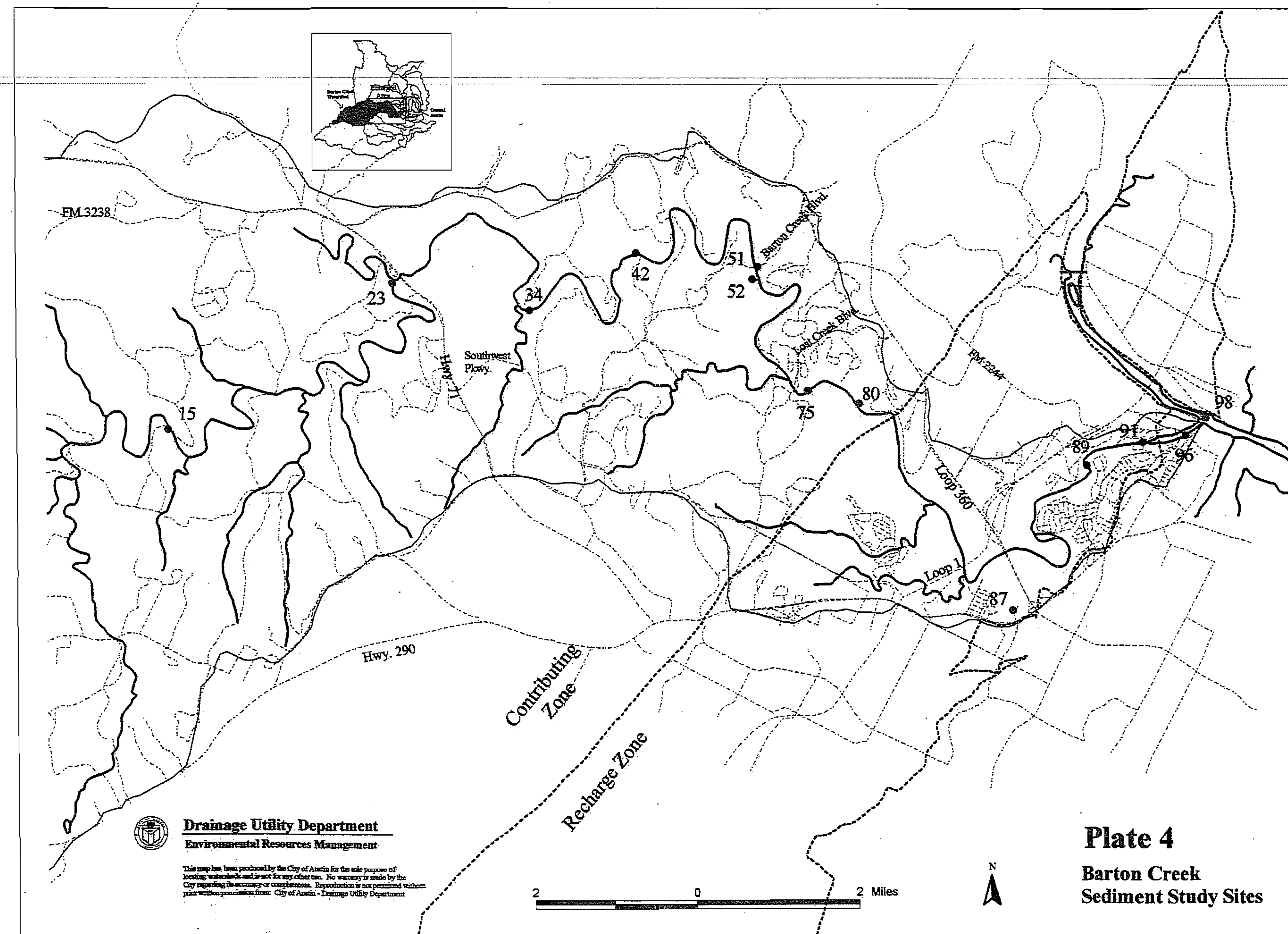
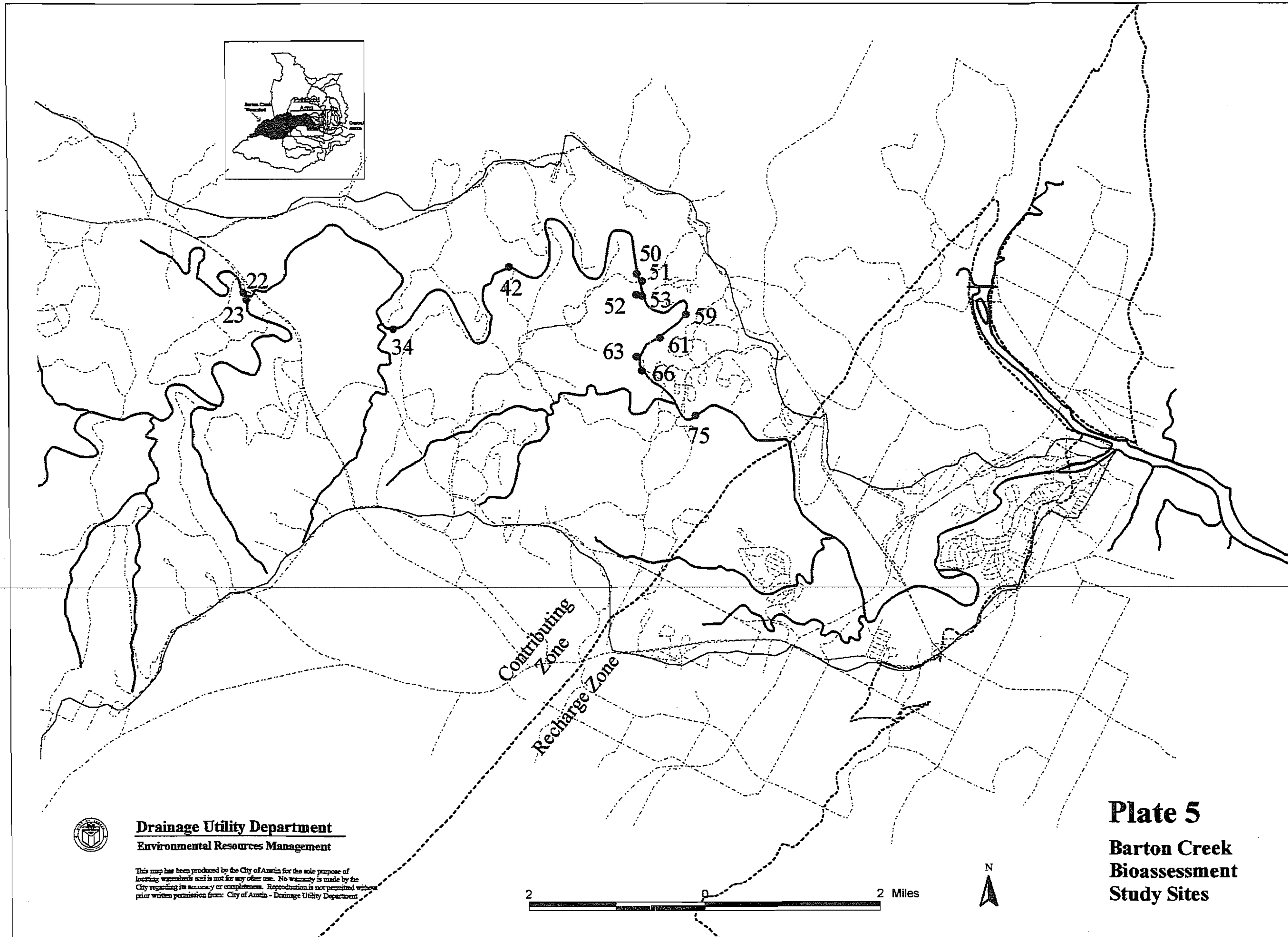


Plate 4

Barton Creek Sediment Study Sites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Contributing Zone
Recharge Zone
Drainage Utility Department
Environmental Resources Management
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Plate 5
Barton Creek Bioassessment Study Sites

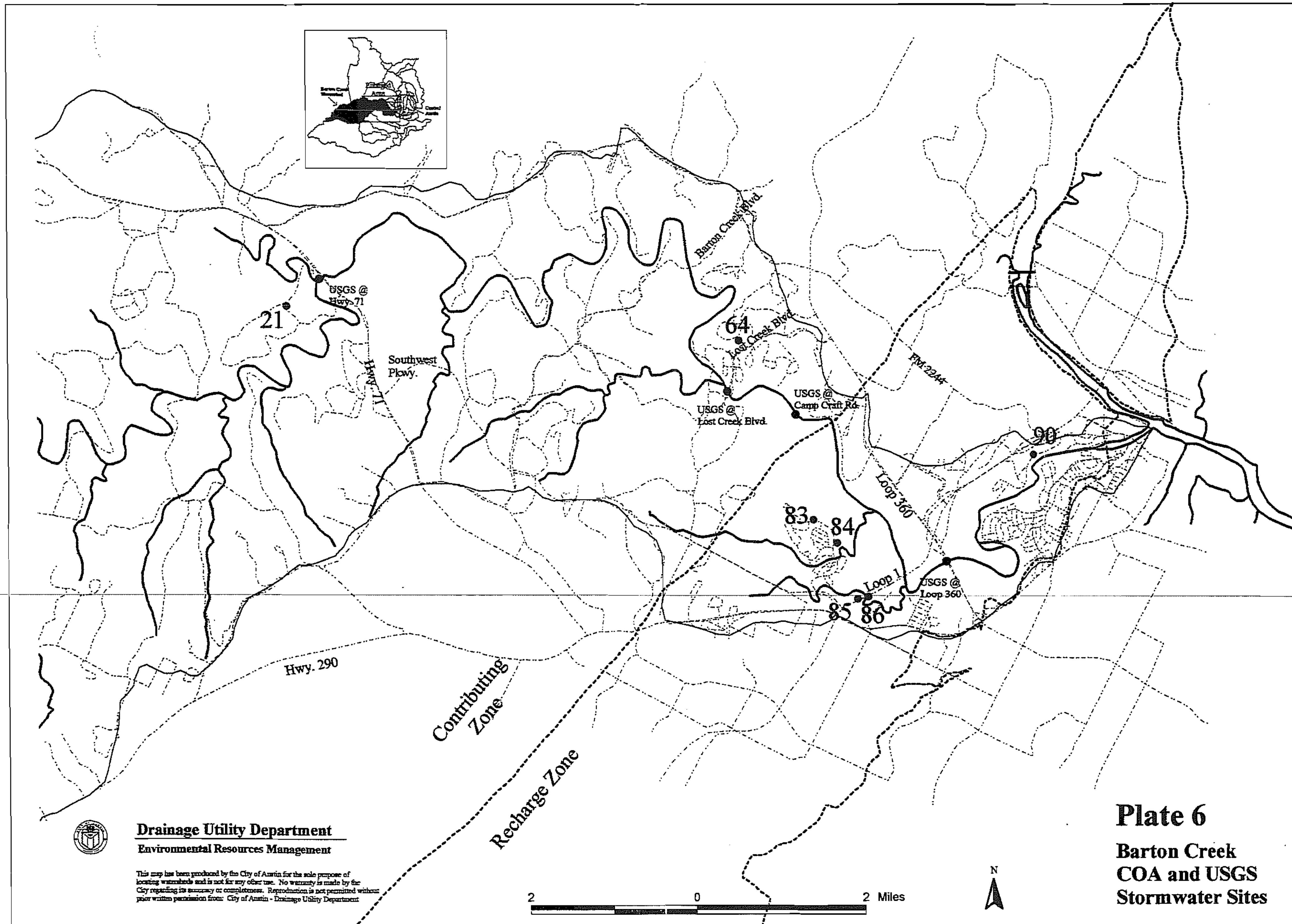

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Plate 6

Barton Creek COA and USGS Stormwater Sites