MEMORANDUM

TO: Mayor and Council

FROM: Victoria J. Li, P.E., Director
Watershed Protection Department

DATE: August 23, 2011

SUBJECT: 2009-2010 Annual Report to U.S. Fish and Wildlife Service

In October 1998, the U.S. Fish and Wildlife Service (the Service) issued the City of Austin an Endangered Species Act Section 10(a)(1)(B) Permit for a period of 15 years. The permit covers incidental take of the federally protected Barton Springs Salamander, *Eurycea sosorum*, that may occur during operation and maintenance of Barton Springs Pool and the adjacent springs located in Zilker Park (Eliza, Old Mill/Sunken Garden, and Upper Barton).

In compliance with the measures set forth in the Habitat Conservation Plan (Section 6 of the permit), the Watershed Protection Department (WPD) has submitted to the Service the report for 2009-2010. This report details the City of Austin's compliance with the 41 measures listed in the permit.

If you have any questions or need additional information, please contact me, 974-9195, or Laurie Dries, WPD Environmental Scientist, at 974-6340.

Victoria Li, P.E., Director
Watershed Protection Department

LD/jr

Attachments: 10(A)(1)(b) Permit Report

CC: Marc A.Ott, City Manager
Sue Edwards, Assistant City Manager
Mike Personett, Assistant Director, Watershed Protection Department
Charlotte Kucera, Biologist, U.S. Fish and Wildlife Service

City of Austin
Founded by Congress, Republic of Texas, 1839
Watershed Protection Department
P.O. Box 1088. Austin. Texas 78767

August 22, 2011

Ms. Charlotte Kucera
U.S. Fish and Wildlife Service
Austin Ecological Services Field Office
10711 Burnet Rd., Suite 200
Austin, Texas 78758
Ph: 512-490-0057

Dear Ms. Kucera:

Enclosed is the annual report for the 10(a)1(B) permit held by the City of Austin for protection of *Eurycea sosorum* for the reporting period October 2009 – September 2010. The report provides a summary of compliance and an assessment of status of both *E. sosorum* and *E. waterlooensis*. Information contained in this report has been previously submitted to you as part of the Biological Assessment for Flood Debris Removal from Barton Springs Pool (USACE SWF-2011-00208). Thus, the report provides assessments of species status based on all available data from 1993-2010. Notes are included for explanation of compliance where needed and amendments for inclusion in new permit tobe issued in 2013

I you have any questions please do not hesitate to contact Laurie Dries, WPD Environmental Scientist, at 512-974-6340, or me at 512-974-9195.

Sincerely,

Victoria J. Li, P.E., Director
Watershed Protection Department

Enclosures

CC: Mike Personett, Assistant Director, Watershed Protection Department

Annual Report October, 2009 — September, 2010
Endangered Species Act Section 10(a)1(B) Permit for the Incidental Take of the Barton Springs Salamander (*Eurycea sosorum*) for the Operation and Maintenance of Barton Springs Pool and Adjacent Springs
Permit # PRT - 839031

Table of Contents

Summary of Compliance

HCP Measure	HCP Measure Compliance
6.1.1 The City of Austin will coordinate the management of salamander habitat areas and be responsible for maintaining information and scientific data on the Barton Springs salamander. The City of Austin will also be responsible for the timely transmittal of information and data to the Service. The City of Austin will submit an annual report to the U.S. Fish and Wildlife Service, Austin Ecological Field Services Office, 10711 Burnet Road, Suite 200, Austin, Texas, 78758. The annual report will address the status of the salamander, provide an analysis of biological data, and review pool maintenance and management activities during the year. The City of Austin will be responsible for all measures in the HCP. In the annual report, each point of the HCP will be addressed. The permit and HCP will be for a period of 15 years. Copies of the annual report will also be submitted to the City Manager and City Council.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The City would like a clarification reporting date. The City will propose changes upon permit renewal.
6.1.2 The City of Austin will make daily visual inspections of all habitat areas (spring sites) and note any problem conditions such as vandalism, trash and debris, introduction of exotic fish or animals, or disturbance of habitat.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.3 When the pool is lowered for cleaning and maintenance, trained City of Austin staff will visually inspect all of the exposed areas of the pool for stranded salamanders. This visual inspection will also include Eliza Spring, Old Mill Spring (Sunken Garden), and Upper Barton Spring. Any stranded salamanders will be moved to permanent water. This measure will be in place upon the issuance of this permit. Until the dam or comparable water control device is installed in the shallow end of the pool, a minimum of four biologists will be present at drawdown to search for stranded salamanders. After installation of the water control device, a minimum of two biologists will be present when the pool is lowered.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: Adjustable gates in the dam serve as water control devices during draw downs of the water level in the Pool. (See 6.1.4 below). The City will propose changes upon permit renewal.

HCP Measure	HCP Measure Compliance
6.1.7 The City of Austin will modify the beach areas in Barton Springs Pool. Portions of the beach areas will be replaced with walkways and wading areas made of exposed aggregate concrete, limestone or other hardened surface. The remaining beach area will be lowered to a minimum depth of 2 meters (6.5 ft.) and additional salamander habitat will be created to mitigate for any loss of habitat. This measure will be in place within six months of permit issuance.	☐ Full Compliance ☐ Partial Compliance ☒ Measure Completed ☐ Measure Needs Amendment Notes: In 1999, substrate elevation of the beach was lowered. A minor amendment to abandon construction of walkways and wading areas, as specified by this measure, was granted to the City by Mr. David Frederick of the Fish and Wildlife Service Austin Ecological Services Field Office on February 24, 1999.
6.1.7a) The City may clean the walkway on an as needed basis (~ 1 per week) using pressure washers (underwater) or other agreed to means.	**a)** ☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: There is no walkway; therefore, cleaning isn't necessary.
6.1.7b) The salamander habitat would be cleaned using only low-pressure hoses or other agreed to means. This cleaning would be done quarterly or as needed to keep the upper 2-3 inches of habitat from becoming embedded with sediment.	**b)** ☐ Full Compliance ☒ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: Despite monthly cleaning, accumulation of excess sediment on beach habitat downstream of the fault zone is an ongoing problem. The presence of the downstream dam reduces the water velocity along substrate such that it is too slow to prevent sediment deposition. Effective maintenance of this area as suitable salamander habitat requires restoration of a more natural stream-like flow regime. A scientific study examining possible dam modifications that would achieve this flow improvement is a funded project described in the Barton Springs Pool Master Plan: Concepts for Improvement and Preservation. In addition, the measure needs to clearly specify use of low water pressure, not low-pressure hoses. The City will propose changes in permit renewal application.

HCP Measure	HCP Measure Compliance
6.1.8 The City of Austin will not drawdown the deep end of the pool if flow in the aquifer is lower than 54 cfs. This measure will minimize the impact of low aquifer levels at the adjacent spring sites, as well as conserve water in the aquifer during low flow conditions.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: Partial drawdowns of water depth are prohibited by this permit, yet they are possible and controllable using the adjustable dam gates and are beneficial for habitat. The City will request an amendment to this measure to specifically include acceptable conditions for partial drawdowns. The City will propose changes in permit renewal application.
6.1.9 The City of Austin will place thin limestone slabs over fissures in the shallow section of the fissures area to minimize impacts from recreational use.	☐ Full Compliance ☐ Partial Compliance ☒ Measure Completed ☒ Measure Needs Amendment Notes: Limestone slabs blocked penetration of sunlight into the fissures, causing deterioration of habitat quality. In addition, slabs were dislodged during floods or disappeared. Their use was abandoned in 2001 with verbal concurrence from the Service. The City will propose changes in permit renewal application.
6.1.10 The City of Austin will lower the water in the deep end of the pool, if necessary, for cleaning only with Service concurrence. The water in the deep end of the pool will not be lowered when the lowering would cause Eliza Spring to go dry. This measure will be in place after the water control structure is installed or an alternative is implemented.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.11 The City of Austin will maintain water over the fissure area during pool drawdown in order to minimize stranding of salamanders. The ability to retain water over the fissures will be in place at the time of permit issuance. The City of Austin will clean the fissure area quarterly or as needed, using a combination of low-pressure hoses and wire hand brushes or other agreed to means. In addition, until the water control structure is in place or the beach area is lowered, the City of Austin will use a spring water sprinkler system to keep the beach area wet during drawdown.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The City will propose changes in permit renewal application.

	at or below 20 cfs. Since no salamanders would be present in dry habitat, disturbance during this aquifer condition would impose the least effects. Therefore, Watershed Protection stream restoration staff will conduct the project when environmental conditions are favorable.
HCP Measure	**HCP Measure Compliance**
6.1.14 The City of Austin will improve the efficiency of the Barton Creek bypass. As currently designed, the cleaning grate at the upstream end of the bypass quickly becomes clogged during storms. The clogging of the grate decreases the efficiency of the bypass and increases the frequency of floods that affect Barton Springs Pool. A more efficient system will be in place within one year of issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: An examination of options to improve water flow through the inlet capacity was completed in 1999 and indicated large-scale replacement might be necessary. The existing grate was modified by removing some cross bars but, concerns about unauthorized public access and safety necessitated replacement of those bars. The City recognizes the need for additional improvement, has included this as one of the short-term projects included in the Barton Springs Pool Master Plan: Concepts for Preservation and Improvement. This work is funded with implementation expected in the winter of 2011.
6.1.15 The City of Austin will implement a program to increase public awareness and community support for the salamander and the Barton Springs portion of the Edwards Aquifer. The SPLASH! Exhibit at Barton Springs Pool will be a major focus of this effort.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The City will propose changes in permit renewal application.
6.1.16 Access to Eliza Spring and Old Mill Spring (Sunken Garden) will be restricted to ensure no disturbance of salamander habitat at these spring areas. These sites will be used as outdoor educational facilities for the study of the biology and ecology of Central Texas springs. These measures will be in place within one year of permit issuance.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:

HCP Measure	HCP Measure Compliance
6.1.19 The City of Austin will deposit $10,000 (in addition to the $45,000 mentioned above) into the conservation fund. This will mitigate for the incidental take that occurred as a result of cleaning the pool and operation from May 30, 1997 (listing effective date) to the date the permit is issued. The fund will be set up and the money deposited within 6 months of permit issuance.	☒ Full Compliance ☐ Partial Compliance ☒ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.20 The City will prohibit the use of high-pressure hoses in salamander habitat.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The text of the measure should be modified to clearly prohibit use of high-pressure *water* not hoses. The City will request amendments with permit renewal application.
6.1.21 The City of Austin may remove woody debris by any methods approved by the Service. All debris will be visually inspected for salamanders before and after removal.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.22 In the event of a flash flood or potential flash flood, it is necessary to prepare Barton Springs Pool area to limit damage. To prepare for such an event, section of fence, trashcans, railings and other items are moved to higher ground. The endangered species biologist for the City of Austin will be notified before Barton Springs Pool is lowered. Barton Springs will not be lowered if flow is lower than 54 cfs or if the City of Austin endangered species biologist indicates that Barton Springs Pool should not be lowered.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The City would like an amendment that specifically allows partial drawdowns under a wider range of discharge conditions. The City will propose changes in permit renewal application.
6.1.23 The City of Austin may clean sediment and debris from the adjacent spring sites using low-pressure hoses or other agreed to means on an as needed basis.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The text of the measure should be modified to clearly prohibit use of high-pressure *water* not hoses. The City will request amendments with permit renewal application.

HCP Measure	HCP Measure Compliance
6.1.28 The City of Austin will prohibit the deliberate disturbance of substrate in the primary salamander habitat. This measure will be effective upon the issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☒ Measure Needs Amendment Notes: The natural disturbance cycles have been altered by dams. Therefore, maintenance of good salamander habitat requires intentional disturbance that mimics that natural system. This is a necessary component of "cleaning" of habitat. More specific delineation of the amount of acceptable anthropogenic disturbance is necessary. The City will propose changes in permit renewal application.
6.1.29 Sediment and debris that is collected during routine cleaning of the pool will be removed from the pool and disposed of properly. This will be accomplished by pumping the material into a vacuum truck for disposal, irrigating the lawns or other agreed to means. The sediment and debris will not be dumped into Barton Creek as a means of disposal. This measure will be effective upon the issuance of this permit.	☐ Full Compliance ☒ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: The City has tried various methods to capture and dispose of sediment and algae dislodged during routine cleaning. None of the methods have been successful. Development of efficient and successful methods for disposing of this material is a funded project within the Barton Springs Pool Master Plan: Concepts for Preservation and Improvements. The City will propose changes in permit renewal application.
6.1.30 Since there is a seasonal rate of turnover in the staff involved in the pool cleaning process, the City of Austin will have professional supervisors direct and document all cleaning procedures at the pool. This measure will be in place upon the issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.31 The City of Austin will ensure that all people working at the pool lifeguards and other staff) are knowledgeable about the salamander. Yearly training will be given to teach staff about the salamanders and the ecology of the Edwards Aquifer springs. This measure will be in place upon the issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.32 The City of Austin will ensure that all people surveying for salamanders are properly trained. The survey work should be done under the terms and conditions of a current scientific permit issued to the City of Austin. This measure will be in place upon the issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:

HCP Measure	HCP Measure Compliance
6.1.36 The City of Austin will, in concurrence with the Service, develop a catastrophic spill response plan for Barton Springs. The new plan will be in place within one year of the implementation of this permit. This plan will address spill prevention, containment, remediation, and salamander rescue.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: The City has completed a comprehensive catastrophic spill response plan. It was submitted to the Austin Ecological Field Services Office on April 22, 2011.
6.1.37 Structural and habitat restoration will occur at Eliza Spring and Old Mill Spring. Habitat restoration will include enhancement of bottom substrate with clean cobble and gravel, and the establishment of native species of aquatic plants. Care will be taken to ensure that non-native invertebrates are not introduced. Old Mill Spring enhancement will include the restoration of full surface flow to the stream. All restoration efforts will be reviewed and approved by the Service before implementation. This work will be completed within two years of the issuance of this permit.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: Restoration of habitat in the spring pool of Old Mill Spring is ongoing. Hand excavation of concrete, is ongoing until bedrock or the spring upwellings are found. Efforts to restore full surface flow to the stream are described in 6.1.13. Native aquatic plants have been re-introduced into the spring pool and stream. Spring pool habitat of Eliza Spring was partially restored in 2004, with the removal of excess rock and sediment, and re-introduction of native aquatic plants. Salamander habitat now consists of natural rocky substrate overlying the concrete floor installed in the 1950s.
6.1.38 The City of Austin will continue to conduct monthly surveys at all spring sites, in compliance with Federal and State Scientific Monitoring Permits.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes:
6.1.39 The City of Austin will form an Advisory Committee of local and regional experts that will meet at least annually to discuss and refine pool maintenance activities. A variety of interests including swimmers, biology and hydrogeology will be represented on this committee. In addition, this committee will review this HCP and make suggestions for needed amendments as deemed necessary. The Advisory Committee will also be responsible for refining the habitat conservation plan through adaptive management. Data collected will be used to adapt management actions. The City of Austin will be responsible for implementation of adaptive management changes.	☒ Full Compliance ☐ Partial Compliance ☐ Measure Completed ☐ Measure Needs Amendment Notes: The Barton Springs Scientific Advisory Committee met formally once in the past year, and continues to review plans for projects in the Barton Springs Pool Master Plan: Concepts for Preservation and Improvements. The Subcommittee of Austin's Environmental, Parks, and Urban Forestry boards includes one member of the BSSAC. The BSSAC has provided assistance with identifying adaptive management activities and will review the new Habitat Conservation Plan prepared for the 2013 permit renewal.

Table 1. Drawdowns of water level of Barton Springs conducted from 2009 – 2010 are listed below. Discharges for flood-associated drawdowns reflect values immediately preceding the flood. An asterisk (*) indicates when increased discharge and surface flow from the flood prevented decreases in water depth in Eliza and Parthenia, respectively.

Date	Site	Water Level Decrease	Event	Aquifer Discharge (cfs)	No. Stranded	No. Re-located	No. Collected Live	No. Died
1/16/10	BSP	50.8"	Flood	77	0	0	0	0
1/16/10	Eliza	16.3"	Flood	77	0	0	0	0
1/29/10	BSP	48.4"	Flood	78	0	0	0	0
1/29/10	Eliza	26.3"	Flood	78	0	0	0	0
2/4/10	BSP	56.9"	Flood	84	0	0	0	0
2/410	Eliza	2.0"	Flood	84	0	0	0	0
3/1/10	BSP	48.5"	Spring Cleaning	90	0	0	0	0
3/1/10	Eliza	15.7"	Spring Cleaning	90	0	0	0	0
9/7/10	BSP	0"	Flood*	86	0	0	0	0
9/7/10	Eliza	0"	Flood*	78	0	0	0	0

During the full drawdown from Spring Cleaning, salamander habitat of Parthenia Spring in Barton Springs Pool was cleaned of loose sediment and debris using approved methods. Although not observed directly, harassment of some salamanders likely occurred during cleaning and recreation. The assumed non-lethal Take from these activities is summarized in Table 2.

Table 2. Assumed Incidental Take from permitted activities conducted October 2009 – September 2010 is presented below. The values are based on Take allotted per activity as delineated in the 10(a)1(B) permit.

Activity	Area	Number/ Event	Assumed Non-Lethal Take	Assumed Lethal Take
Cleaning	Fissures	1 cleaning	0-19	0
Flood Preparation	Eliza Spring and Fissures	3	0-36	0
Recreation	Barton Springs Pool	Annual	100	20
		Total	**0-155**	**20**

rivers and streams (Lampert and Sommer 1997 pg. 34; Giller and Malmqvist 1998 pg. 31-32; Wetzl 2001 pg. 151-164). In addition, the maximum concentration of oxygen that can be dissolved in water is inversely dependent on water temperature (Boyle 1662; Levine 1978; Wetzl 2001); the warmer the water, the less dissolved oxygen it can hold. Since dissolved oxygen and temperature can influence every aspect of the aquatic community (Cushing and Allan 2001; Giller and Malmqvist 1998 references therein; Wetzl 2001 and references therein), drought-related reductions in spring discharge can have strong effects on resident flora and fauna.

Dissolved oxygen sustains animal life because it is used to convert food into metabolic energy (Eckert et al.1973). Both survival and reproduction depend on metabolic energy; its allocation to each depends on the amount available (Fig. 1) and the life history of the animal. For long-lived animals that reproduce more than once in a lifetime, such as *E. sosorum,* when dissolved oxygen is high, metabolic energy can be created in abundance, and allocated to both survival *and* reproduction (Pianka 1983; Krebs and Davies 1993). Conversely, when dissolved oxygen is low, metabolic energy is limited and generally will be allocated to survival. Reproduction is delayed until environmental conditions improve. This gives rise to two predictions for *E. sosorum* that can be useful in predicting likely effects of drought. When dissolved oxygen is high, which occurs when discharge is higher, these salamanders are expected to reproduce, causing juvenile abundance to increase. Conversely, when dissolved oxygen falls below a reproduction threshold, juvenile abundance should decrease. Ultimately, when dissolved oxygen falls below the adult survival threshold, there should be a decrease in adult abundance. Thus, dissolved oxygen is likely one of the major indicators of salamander population status and trend and it is explicitly considered in this assessment. Similarly, when water temperature is lower, dissolved oxygen will be higher, also potentially promoting salamander reproduction and increases in juvenile abundance (Gillespie 2011).

Eliza Spring

Abundance, Density, Recruitment, and Effects of 10(a)1(B) Permit Implementation

A census of the salamander population in Eliza Spring has been obtained roughly every month since 1995. These data suggest that this site has come to harbor the most robust population of *E. sosorum*. Abundance at this site likely provides the best information from which to infer population status because of two features. One, the smaller size of this spring (~ 800 sq. ft.) allows the entire surface habitat to be searched during every survey. Two, the presence of a concrete floor below surface substrate limits salamander access to the sub-surface, allowing for greater detection of salamanders if present.

Mean annual salamander abundance for the period of record varies widely, from a low of 1.6 in 2000 to a high of 703.4 in 2008. Salamander abundance in Eliza Spring is significantly higher after implementation of the federal 10(a)1(B) permit ($U = 734.5$, $z = -3.292$, $p = 0.001$) than before. However, closer examination reveals that abundance differs significantly among three time periods: before permit implementation (1995 – 1997), after permit implementation but before habitat reconstruction (1998-2002), and after habitat reconstruction (2003-2010) (Kruskal-Wallis $H = 89.832$, $p < 0.0001$). Limiting the comparison to the time period before habitat reconstruction reveals that abundance was significantly lower after permit implementation (1998 – 2002) ($U = 255.5$, $z = -2.897$, $p = 0.004$; Table 3).

Habitat Reconstruction

There have been dramatic changes in abundance and density in this site due to anthropogenic and natural factors. The positive anthropogenic factor was habitat reconstruction of the spring pool in 2003 (City of Austin 2004). The changes in habitat included restoring more natural, shallow

Physical characteristics in the spring pool after habitat reconstruction (7/2003 – 12/2009) confirm the importance of two factors to *E. sosorum*. Salamander density in Eliza Spring is significantly positively correlated with flow velocity, and negatively correlated with percent sediment cover and water depth (Table 4). Percent sediment cover represents the sedimentary layer overlying substrate and is positively correlated with water depth; as water depth decreases, percent sediment cover also decreases. Mean values of sediment and water depth after reconstruction are more typical of shallow, flowing streams (sediment = 0.6 in. ± 0.6 S.D.; water = 12.9 in. ± 3.1) in which the majority of *Eurycea* species are found (Wells 2007, Petranka 1998). These results support previous inferences (City of Austin 2004) that *E. sosorum* fares better in habitats with flowing water and less sediment-laden substrate.

Table 4. Spearman Rank correlation coefficients (ρ) and significance values (p) of habitat and *E. sosorum* density in Eliza Spring from July 2003 through December 2010 are presented below. Mean ± Standard Deviation of each variable is also listed. Water and sediment depth are listed in inches, velocity in feet per second.

Variable Mean ± SD	Salamander Density 348.9 ± 274.5	Sediment Depth 0.68 ± 0.51 in.	% Sediment Cover 36.2 ± 23.2
Flow Velocity 0.57 ± 0.55 ft./sec.	ρ=0.067 p= 0.016	ρ=-0.058 p= 0.581	ρ= 0.320 p= 0.002
Water Depth 15.2 ± 8.3 in.	ρ=-0.305 p=0.024	ρ= 0.219 p= 0.002	ρ= 0.471 p=0.0003
% Sediment Cover 36.2 ± 23.2	ρ=-0.166 p= 0.011	ρ= 0.173 p= 0.002	•

Drought

In Eliza Spring, the most detrimental "semi-natural" factor was the persistent decrease in aquifer discharge of June 2008 – September 2009. Its effects on the salamander population were statistically significant decreases in total salamander abundance and density relative to the 2003 – May 2008 period (abundance: $U = 196.5$, z = -2.253, p = 0.024; density: $U = 201.5$, z = -02.169, p = 0.030; Table 5). Juvenile and adult abundances were significantly lower during the drought (Juv.: U = 172.0, z =z –2.662, p = 0.0078; Adult: $U = 131.5$, z = -3.286, p = 0.001), while young adult abundance was not ($U = 268.5$, z = -0.960, p = 0.337) (Fig. 5).

The drought's effects on habitat were evident in the reduction of dissolved oxygen, increases in water temperature, and decreases in current speed. Mean water temperature increased from 69.8°F (21.5°C) to 70.7°F (20.0°C) during the drought, and mean velocity decreased significantly (U = 36.50, z = -2.960, p = 0.0031) from 0.851 ft/sec. (±0.168 s.e.) to 0.292 (±0.050 s.e.). Mean dissolved oxygen concentration was 4.3 mg/L (±0.124 s.e.), which includes values as low as 3.88mg/L (Table 5). The mean is below the 28-day LC_5 threshold (4.5 mg/L) for adult survival of *E. nana*, and below the 60-day threshold (4.44 mg/L) at which growth of juvenile *E. nana* is compromised (Woods et al. 2010).

The drought began to break with the rainfall and increase in groundwater discharge in October of 2009. Within two weeks, abundance of young adult and adult salamanders jumped from 27 and 14, to 139 and 134, respectively. No juveniles were found. November abundances showed increases in all size classes, 12 juveniles, 230 young adults, and 154 adults. Since reproduction, hatching, and juvenile development require more than two months, these increases suggest that some adults and young adults found places to take refuge from the effects of drought, and were not detected during monthly surveys. However, abundances have not increased to the 2008 pre-

Table 6. Results of nonparametric Mann-Whitney U statistical tests comparing salamander abundance and density, and dissolved oxygen concentration during (June 2008 through September 2009) and after the drought (October 2009 through December 2010) are presented below. Probability values significant at ∝ = 0.05 are indicated by an asterisk (*).

Variable	*U*	Z-value	p-value
Abundance			
Total	57.0	-0.998	0.320
Adults	49.0	-1.442	0.149
Young Adults	46.0	-1.609	0.107
Juveniles	31.5	-2.413	0.016*
Density			
Total	53.0	-1.220	0.222
Adults	56.0	-1.054	0.291
Young Adults	44.0	-1.720	0.086
Juveniles	28.0	-2.607	0.009*
DO	0.0	-4.031	<0.0001*

Despite the recent severe drought, Eliza Spring remains the best habitat and harbors the largest and most robust *E. sosorum* salamander population in the Barton Springs complex. This population likely has the best potential to weather adverse conditions. It provides our best opportunity to understand how the species responds to environmental change, both natural and anthropogenic, and therefore, how to best protect and foster recovery of *E. sosorum*.

Parthenia Spring

The salamander population in Parthenia Spring (in Barton Springs Pool) has been monitored since 1993. This site has the largest area of potential habitat (~15,000 sq. ft.) composed of natural caves, crevices, and fissures (~4,000 sq. ft.), and the "beach" (USFWS 1998), 11,000 square feet of a manmade shelf of compacted caliche, gravel, and cobble. The size of potential habitat and human access to small cracks is limited and precludes conducting complete surveys of surface habitat as in the other sites of the Barton Springs complex. Since survey methods have varied in type, area surveyed, and survey effort (Fig. 6), the influence of systematic error on each sample of salamander abundance is likely greater in this site (Scheiner and Gurevitch 2001). Patterns of changes in abundance and density were examined to understand how the population responds to environmental changes and population status. The management of the aquatic environment of the Pool has changed considerably since listing of *E. sosorum* and implementation of the Habitat Conservation Plan associated with the 10(a)1(B) permit for Barton Springs (USFWS 1998). For example, chemical cleaners are no longer used, Pool drawdowns are restricted, and habitat areas are cleaned by federally permitted biologists only. Therefore, included in the assessment below is an examination of whether changes in salamander populations are related to these changes in habitat management.

Abundance, Density, Recruitment, and Barton Springs' Discharge

Eurycea sosorum abundance varies among the habitat locations within Barton Springs Pool (Fig. 7). From 1993 to the present, the largest proportion of salamanders occurred in and around the caves and fissures from which the groundwater emanates (Fig. 7) regardless of survey method. These proportions are largely independent of changes in density, and are not simply a consequence of greater or fewer salamanders in total. However, regular surveys have included only the upstream portion of the beach (Beach 1) or have not included the beach at all. Salamander abundance data for beach areas outside of regular survey areas are from experimental drawdowns conducted from 1997 – 1998, and a single survey in December 2009.

Table 7 (cont.). Mean, standard deviation (S.D.), standard error (s.e.), and sample size (N) of *E. sosorum* salamander abundance and density in Parthenia Spring for each year of record are listed below. Minimum (Min.) and Maximum (Max.) salamander abundance are also listed. Density could not be calculated for April 1998 – July 2003 because exact area surveyed is unknown.

Parthenia	Abundance (#)						Density (#/sq ft)			
Year	Mean	S.D.	s.e.	N	Min.	Max.	Mean	S.D.	s.e.	N
2005	111.0	84.5	32.0	7	16	236	0.042	0.032	0.012	7
2006	86.9	124.6	41.5	9	1	300	0.034	0.045	0.015	9
2007	27.8	16.0	6.5	6	9	55	0.011	0.007	0.003	6
2008	177.6	110.6	36.9	9	76	447	0.081	0.042	0.014	9
2009	28.7	22.5	8.5	7	5	73	0.010	0.010	0.004	7
2010	54.9	33.8	11.9	8	13	111	0.013	0.006	0.002	8
After Phase I Reconstruction	86.2	95.2	14.0	46	1	447	0.034	0.039	0.006	46
After HCP	55.3	70.0	6.7	108	1	447	0.032	0.035	0.004	180
1993-2010	43.0	60.2	4.8	161	1	447	0.034	0.031	0.003	116

Habitat Reconstruction

Concerted efforts to improve salamander habitat in Parthenia Spring were begun in 2004 based on the beneficial effects of similar changes in Eliza Spring (City of Austin 2004). The major goal of habitat reconstruction is to restore a more natural flow regime from Parthenia Spring and throughout Barton Springs Pool, as was done in Eliza Spring. Higher flow velocities of creeks and rivers are the dominant feature distinguishing them from lakes and ponds (Leopold et al. 1992). Flowing water influences every part of the aquatic ecosystem (Wetzl 2001; Giller and Malmqvist 1998), from the amount of sediment (Nowell and Jumars 1984) and type of algae (Poff et al. 1990; Reiter and Carlson 1986; Blum 1960) to the community of invertebrates and vertebrates (Vogel 1994). Faster, unidirectional water flow naturally favors growth of tightly attached algae (Stevenson 1983; Korte and Blinn 1983; Fritsch 1929), favors a diversity of stream-adapted invertebrates (Hynes 1972), and helps maintain high water quality (Spellman and Drinan 2001). The dams impounding Parthenia Spring have shifted the ecological character to a more lake-like condition less suitable for stream-adapted *E. sosorum*. Drawing down water level temporarily restores increased flow velocity, which could improve flow regime in salamander habitat. Hence, a series of experimental partial drawdowns were designed to examine whether habitat quality would improve and salamander abundance would change.

A series of monthly partial drawdowns were conducted from 2004-2005 (City of Austin 2005). Draw downs were coupled with manual efforts to reopen clogged spring flow paths by flushing sediment, small pebbles, and other obstructions from fissures and the mouths of the springs with gentle flow of re-circulated spring water. As of December 2006, there were statistically significant decreases in mean sediment depth in sections in front of two of the caves at the spring mouth, Little Main (U = 53.5, z = -2.329, p = 0.02) and Side Spring (U = 50.0, z = -2.309, p = 0.02). These reductions have persisted through 2010 despite bouts of floods in 2007 and 2010 (Little Main: U = 153.0, z = -2.730, p = 0.006; Side Spring: U = 158, z = -2.192, p = 0.03). Percent sediment cover was not significantly less in 2006 after habitat reconstruction (U = 51.0, z = -0.927, p = 0.35), although there is a marginally significant decrease by the end of 2010 (U = 202.0 z = -1.827, p = 0.07). This likely reflects the variability of sediment cover caused by periods when floods entered Barton Springs Pool.

Salamander abundance and density increased significantly by December 2006, after habitat reconstruction (Abundance: U = 2158.5, z = -2.871, $p_{\alpha=0.025}$ = 0.004; Density: U = 1131.0, z = -

Table 8 (cont.). Mean, standard deviation (S.D.), and standard error (s.e.) of dissolved oxygen (DO) and *E. sosorum* abundance and density in Parthenia Spring from July 2003 – May 2008 before the severe drought, from June 2008 – September 2009 during the severe drought, and from October 2009 – December 2010 after the drought. Totals and values for each size class are included. Minimum (Min.) and Maximum (Max.) salamander abundances and dissolved oxygen concentrations are also listed.

No Drought 10/09-12/10									
Total	49.5	32.1	10.2	10	13	111	0.010	0.006	0.002
Juvenile	14.3	13.2	4.2	10	2	41	0.003	0.002	0.001
Young Adult	24.4	14.4	4.5	10	4	51	0.006	0.003	0.001
Adult	9.9	7.1	2.2	10	1	22	0.002	0.001	0.0005
DO	6.40	0.52	0.16	10	5.80	7.24	n/a	n/a	n/a

Old Mill Spring

Salamander abundance estimates have been obtained from Old Mill Spring (Sunken Garden) since 1995. A single sample was taken in 1995 and no samples were taken in 1996. In 1998, salamanders of a potentially different species were identified as *E. waterlooensis*, which was subsequently described in 2001 (Hillis et al. 2001). *Eurycea waterlooensis* abundance has been recorded separately from 1998 to the present; all salamanders found in 1995 and 1997 are identified as *E sosorum*. Until 2004, abundance of both *E. sosorum* and *E. waterlooensis* were generally higher in this site relative to the other three (City of Austin 2004, 2005, 2006, 2007).

Total *E. sosorum* abundance and density in Old Mill Spring is significantly lower than in Eliza and Parthenia Springs (abundance: Kruskal-Wallis $H = 37.53$, $p < 0.0001$; density: $H = 133.02$, $p < 0.0001$; Table 9; Figs. 13, 14). Based on data from 2003 to the present, when reproduction occurs in this site (Fig. 15), it is during non-drought periods. The number of juveniles is positively correlated with number of young adults three months later ($\rho = 0.663$ $z = 2.901$, $p_{\alpha=0.05} = 0.005$), as is number of young adults with number of adults three months later ($\rho = 0.669$ $z = 3.068$, $p_{\alpha=0.05} = 0.003$; Fig. 16).

Abundance, Density, and Effects of 10(a)1(B) Permit Implementation

Comparison of *E. sosorum* abundance indicates a significant decrease after issuance of the federal 10(a)1(B) permit ($U = 980.5$, $z = -3.231$, $p = 0.0012$). However, this result does not accurately reflect changes in *E. sosorum* alone because prior to 1998 when *E. waterlooensis* was described, all *Eurycea* observed in this site before 1998 were classified as *E. sosorum*. Thus, data collected from 1995 – 1997 include an unknown number of *E. waterlooensis*. To make an appropriate, unbiased comparison of potential effects of implementation of the federal permit, numbers of *E. sosorum* and *E. waterlooensis* observed after permit issuance were combined (Table 9). Comparison of abundance and density of all *Eurycea* salamanders found in Old Mill Spring before and after issuance do not differ significantly (Abundance: $U = 180.5$, $z = -1.478$, $p = 0.14$; Density: $U = 174.5$, $z = -1.349$, $p = 0.18$; Table 10). This suggests issuance of the permit has not been detrimental to abundance and density of resident *Eurycea*.

Habitat Reconstruction

Non-invasive habitat reconstruction in this site has been ongoing since 2006. Available habitat area has increased with the elimination of unnatural outflow through an underground pipe, widening and lowering the elevation of the outflow stream, and removing several feet of rock, trash, and accumulated sediment in the spring pool. These changes allow for greater flow velocities under all conditions, and more wetted surface habitat during low Barton Springs' discharge conditions. Despite the demonstrated benefits of similar habitat reconstruction in Eliza Spring and theoretical support for expected improvements, there is no evidence of a significant effect of these changes on *E. sosorum* abundance or density in Old Mill Spring (abundance: U = 388.5, z = -0.310, $p_{\alpha=0.05}$ = 0.756; density: (U = 376.50, z = -0.465, $p_{\alpha=0.05}$ = 0.641; Table 9).

Drought

The droughts of October 2005 to October 2006 and of June 2008 to September 2009 were accompanied by biologically significant decreases in dissolved oxygen and increases in water temperature, as well as lack of detectable flow velocity in the spring pool (City of Austin, unpublished data). The *E. sosorum* population in this site was affected more severely by the droughts than those in Eliza and Parthenia Springs. There were 6 and 11 consecutive months during the 2005 - 2006 and 2008 - 2009 droughts, respectively, where no salamanders were found (Table 11; Fig. 15). Total *E. sosorum* abundance and density were significantly lower during the droughts (abundance: U=137.5, z=-5.088, p<0.0001; density: U=144.5, z=-4.999, p<0.0001). Dissolved oxygen was also significantly lower during droughts (U=447.5, z=-4.674, p<0.0001; Fig. 15). Water temperature during the drought periods was significantly higher (U=802, z=-2.141, p<0.0001) than during non-drought. When D.O. is at or below 4.0 mg/L, number of adults is significantly positively correlated with number of juveniles three months later (ρ=1.000, z=2.000, $p_{\alpha=0.05}$=0.045). In other words, when dissolved oxygen is below 4.0 mg/L and adult abundance is at or near zero, juvenile counts are lower, compared to when adult counts are greater than zero. There is a correlation between adult and juvenile counts 3 months later, meaning a low number of adults is correlated with few or no juveniles under these conditions. When there are no juveniles, there is no opportunity for recruitment into the existing young adult population, so correlation is not significant (ρ=0.775, z=1.550, $p_{\alpha=0.05}$=0.147). This suggests that during the recent droughts no reproduction or recruitment were observed in this site despite efforts to augment DO in the spring pool after it dropped below 4 mg/L. Dissolved oxygen augmentation was accomplished by re-circulating water through a pump and allowing it to cascade back into the Pool, entraining additional oxygen in the water and increasing flow velocity. Measurements of dissolved oxygen during DO augmentation indicate this method was successful in general although warmer water temperatures during the day limited the total amount of oxygen that could be added to the water without creating unnatural supersaturation.

Table 12. Mean, standard deviation (S.D.), and standard error (s.e.) of *E. sosorum* salamander abundance and density in Upper Barton Spring for each year of record are listed below. Minimum (Min.) and Maximum (Max.) salamander abundance are also listed. Density is number per square foot. Surface habitat in this spring site was dry from Sept. 1999 – May 2000, Nov. 2003 – Feb. 2004, Nov. 2005 – Jan. 2007, June 2008 to Oct. 2009.

Upper Barton	Abundance (#)						Density (#/sq ft)		
Year	Mean	S.D.	s.e.	N	Min.	Max.	Mean	S.D.	s.e.
1997	5.8	5.3	2.4	5	1	14	0.013	0.012	0.005
1998	1.9	1.3	0.4	9	0	4	0.004	0.003	0.001
1999	0.6	0.7	0.2	10	0	2	0.002	0.001	0.001
2000	1.9	3.2	1.1	8	0	9	0.011	0.008	0.004
2001	5.4	5.0	1.6	10	0	14	0.012	0.011	0.004
2002	5.0	3.6	1.1	10	0	12	0.011	0.008	0.003
2003	2.4	2.1	0.6	11	0	5	0.006	0.004	0.001
2004	5.8	5.1	1.6	10	0	14	0.016	0.010	0.004
2005	3.1	3.3	1.3	7	0	9	0.010	0.007	0.003
2007	4.8	5.1	1.6	10	0	13	0.010	0.010	0.003
2008	9.0	13.1	4.4	9	0	30	0.051	0.036	0.018
2009	9.0	9.9	7.0	2	2	16	0.013	0.012	0.009
2010	28.1	27.0	8.1	11	4	100	0.043	0.042	0.013
1997-2010	5.9	11.6	1.0	124	0	100	0.015	0.022	0.002

Table 13. Mean, standard deviation (S.D.), and standard error (s.e.) of abundance and density of juvenile, young adult, and adult *E. sosorum* salamanders in Upper Barton Spring for all years of record are listed below. Minimum (Min.) and Maximum (Max.) salamander abundance are also listed. Density is number per square foot. Data for young adult and adult size classes are a subset comprising 2003 – 2010.

Upper Barton	Abundance						Density		
Size class	Mean	S.D.	s.e.	N	Min.	Max.	Mean	S.D.	s.e.
Juvenile (<1" TL:1997–2010)	1.7	6.5	0.6	124	0	62	0.004	0.012	0.001
Adult (≥ 1" TL):1997-2010)	4.1	6.2	0.6	124	0	37	0.011	0.013	0.001
Young Adult (1-2" TL:2003–2010)	5.4	7.1	1.1	43	0	34	0.010	0.013	0.002
Adult (≥ 2" TL:2003–2010)	2.3	2.8	0.4	43	0	10	0.006	0.006	0.001

Although there is no evidence of recruitment in the *E. sosorum* population in Upper Barton Spring (Fig. 37), salamanders continue to be present and reproduce at this site.

Drought

Surface habitat of Upper Barton Spring is dry when Barton Springs' discharge drops below ~ 40ft^3/s. No live or dead salamanders have been found once surface water disappears, yet, salamanders are found when surface flow returns. Consequently, it is difficult to ascertain how drought affects this population. The fate of these salamanders when surface habitat is dry is unclear; they may die, remain underground, or migrate to another site during these periods. To begin to understand what happens to the resident salamanders during dry periods, City of Austin staff marked salamanders found in Upper Barton Spring from January 2007 through April 2008, while there was continuous water flow in surface habitat. During this period 48 *E. sosorum* in Upper Barton Spring were given a fluorescent elastomer mark by City of Austin staff. Nine of the 48 salamanders marked were recaptured at later dates (19% recaptured)(Table 14). Six salamanders marked in January and February of 2008 were recaptured in Upper Barton Spring 1

Table 15. Mean, standard deviation (S.D.), and standard error (s.e.) of abundance and density of *E. waterlooensis* salamanders in all spring sites from 1998 – 2010 are listed below. Minimum (Min.) and Maximum (Max.) salamander abundance are also listed.

	Abundance (#)						Density (#/sq ft)		
Year	**Mean**	**S.D.**	**s.e.**	**N**	**Min.**	**Max.**	**Mean**	**S.D.**	**s.e.**
				Old Mill Spring					
1998	0.7	1.0	0.3	9	0	2	0.0005	0.001	0.0003
1999	0.3	1.0	0.3	9	0	3	0.0003	0.001	0.0003
2000	0.5	0.8	0.3	8	0	2	0.001	0.001	0.0004
2001	9.1	12.4	3.9	10	0	37	0.008	0.009	0.003
2002	9.1	6.6	2.2	9	1	21	0.007	0.005	0.002
2003	15.5	15.3	4.8	10	0	43	0.012	0.011	0.004
2004	8.8	5.3	1.8	9	0	16	0.007	0.004	0.001
2005	1.5	1.8	0.6	8	0	5	0.001	0.001	0.0005
2006	0.4	0.7	0.2	9	0	2	0.0003	0.001	0.0002
2007	0.2	0.4	0.2	6	0	1	0.0001	0.0003	0.0001
2008	1.8	2.4	0.8	8	0	6	0.001	0.002	0.001
2009	0	0	0	12	0	0	0	0	0
2010	0.1	0.3	0.1	11	0	1	0.00005	0.0002	0.00005
1998-2010	3.8	7.8	0.7	118	0	43	0.003	0.006	0.001
				Eliza Spring					
1998	0	0	0	9	0	0	0	0	0
1999	0	0	0	9	0	0	0	0	0
2000	0	0	0	10	0	0	0	0	0
2001	0	0	0	8	0	0	0	0	0
2002	0	0	0	8	0	0	0	0	0
2003	0	0	0	10	0	0	0	0	0
2004	1.1	1.1	0.4	7	0	3	0.001	0.001	0.001
2005	1.4	2.3	0.7	10	0	6	0.001	0.003	0.001
2006	3.7	4.5	1.4	10	0	12	0.005	0.006	0.002
2007	1.5	1.6	0.5	11	0	5	0.002	0.001	0.001
2008	1.0	1.5	0.4	12	0	4	0.001	0.002	0.001
2009	0.1	0.3	0.1	10	0	1	0.0001	0.0004	0.0003
2010	0	0	0	8	0	0	0	0	0
1998-2010	0.73	1.9	0.2	122	0	12	0.001	0.003	0.0003
				Parthenia Spring					
1998	0.1	0.3	0.1	10	0	1	n/a	n/a	n/a
1999	0	0	0	10	0	0	n/a	n/a	n/a
2000	0	0	0	9	0	0	n/a	n/a	n/a
2001	0	0	0	7	0	0	n/a	n/a	n/a
2002	0.3	0.5	0.2	9	0	1	n/a	n/a	n/a
2003	0.6	0.9	0.3	8	0	2	0.0003	0.0004	0.0002
2004	0.1	0.3	0.1	9	0	1	0.00005	0.0001	0.00005
2005	0.1	0.4	0.1	7	0	1	0.00005	0.0001	0.00005
2006	0.3	0.7	0.2	9	0	2	0.0001	0.0003	0.00009
2007	0.7	0.8	0.3	6	0	2	0.0003	0.0004	0.0002
2008	0.2	0.7	0.2	9	0	2	0.0001	0.0003	0.0001
2009	0.1	0.4	0.1	7	0	1	0.00004	0.0009	0.00004
2010	1.1	2.0	0.8	7	0	5	0.0003	0.0004	0.0001
1998-2010	0.3	0.7	0.1	107	0	5	0.0001	0.0003	0.00004

References

Blum JL. 1960. Alga populations in flowing waters. Special Publications of the Pymatuning laboratory of field biology 2: 11-21.

Boyle, 1662. The Boyle Papers. BP 9, fol. 75v-76r. Royal Society Centre for History of Science.

City of Austin. 2004. Endangered Species Act section 10(a)(1)(B) permit for the incidental take of the Barton Springs Salamander (*Eurycea sosorum*) for the operation and maintenance of Barton Springs Pool and adjacent springs. Permit #PRT-839031. Annual Report 1 October 2002 - 30 September 2004. Austin (TX): City of Austin Watershed Protection and Development Review Department.

City of Austin. 2005. Endangered Species Act section 10(a)(1)(B) permit for the incidental take of the Barton Springs Salamander (*Eurycea sosorum*) for the operation and maintenance of Barton Springs Pool and adjacent springs. Permit #PRT-839031. Annual Report 1 October 2004 - 30 September 2005. Austin (TX): City of Austin Watershed Protection and Development Review Department.

City of Austin. 2006. Endangered Species Act section 10(a)(1)(B) permit for the incidental take of the Barton Springs Salamander (*Eurycea sosorum*) for the operation and maintenance of Barton Springs Pool and adjacent springs. Permit #PRT-839031. Annual Report 1 October 2005 - 30 September 2006. Austin (TX): City of Austin Watershed Protection and Development Review Department.

City of Austin. 2007. Endangered Species Act section 10(a)(1)(B) permit for the incidental take of the Barton Springs Salamander (*Eurycea sosorum*) for the operation and maintenance of Barton Springs Pool and adjacent springs. Permit #PRT-839031. Annual Report 1 October 2006 - 30 September 2007. Austin (TX): City of Austin Watershed Protection and Development Review Department.

City of Austin. 2010. Biological Assessment Barton Springs Flood Debris Removal and Bypass Repairs, Austin, Texas. City of Austin Watershed Protection Department. Prepared for U.S. Army Corps of Engineers Ft. Worth District Office. April 21, 2010. pg 30.

Chippindale, PT 2010. Genetic variation and population structure in the Barton Springs Salamander, *Eurycea sosorum*. The Barton Springs Salamander Conservation Fund Project Report to the City of Austin, Texas. 51 p.

Cushing CE, Allan JD. 2001. Streams: Their Ecology and Life. San Diego (CA): Academic Press. p. 28-29.

Eckert R, Randall D, Augustine G. 1988. Animal Physiology: Mechanisms and Adaptations. New York (NY): W. H. Freeman and Company. 683 p.

Fritsch FE. 1929. The encrusting algal communities of certain fast flowing streams. New Phytologist 28: 165-196.

Giller PS, Malmqvist B. 1998. The Biology of Streams and Rivers. Oxford (UK): Oxford University Press. p. 31-32.

Reiter MA, Carlson RE. 1986. Current velocity in streams and the composition of benthic algal mats. Canadian Journal of Fisheries and Aquatic Sciences 43: 1156-1162.

Scheiner SM, Gurevitch J. 2001. Design and Analysis of Ecological Experiments. Second edition. Oxford (NY): Oxford University Press.

Smith B, Hunt B. 2010 A comparison of the 1950s drought of record and the 2009 drought, Barton Springs segment of the Edwards Aquifer, Central Texas: Gulf Coast Association of Geological Societies Transactions 60:611-622.

Spellman FR, Drinan JE. 2001. Stream Ecology and Self-Purification: an Introduction. Lancaster (PA): Technomic Publishing Co. Inc.

Stevenson RJ. 1983. Effects of current and conditions simulating autogenically changing microhabitats on benthic diatom immigration. Ecology 64: 1514-1524.

Takahashi MK, Pauley TK. 2010. Resource allocation and life history traits of *Plethodon cinereus* at different elevations. American Midland Naturalist 163(1): 87-94.

U.S. Fish and Wildlife Service (USFWS). 1998. Endangered Species Act section 10(a)(1)(B) permit for the incidental take of the Barton Springs Salamander (*Eurycea sosorum*) for the operation and maintenance of Barton Springs Pool and adjacent springs. Permit #PRT-839031.

U. S. Geological Survey. 1990. Water Resources Data. Texas, Water Year 1990: U. S. Geological Survey Water-Data Report. TX 90.

U. S. Geological Survey. 2005-2009. Water Resources Data. Texas, Water Years 2005-2009: U. S. Geological Survey Water-Data Reports. TX 05-08.

Vogel S. 1994. Life in Moving Fluids: the Physical Biology of Flow. Princeton (NJ): Princeton University Press.

Wells, KD. 2007. The Ecology and Behavior of Amphibians. University of Chicago Press, Chicago, IL, USA.

Wetzl, RG. 2001. Limnology: Lake and River Eosystems. Third edition. San Diego (CA): Academic Press.

Woods, HA, Poteet, MF, Hitchings, PD, Brain, RA, and Brooks, BW. 2010. Conservation physiology of the plethodontid salamanders *Eurycea nana* and *E. sosorum*: response to declining dissolved oxygen. Copeia 4:540-553.

Figures

Figure 1.

Dissolved Oxygen, Metabolism, and Resource Allocation. Dissolved oxygen is the necessary first step in generating metabolic energy for animals. Some long-lived animals can delay reproduction when metabolic energy is limited, such as when dissolved oxygen is limited.

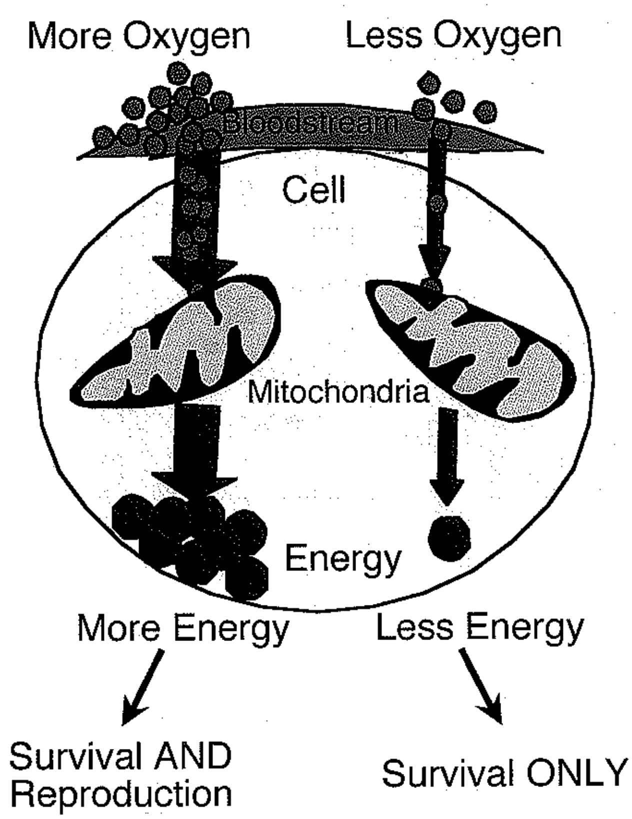

Figure 3.
Eurycea sosorum density from 2003 to 2010. Lines connect data points from consecutive monthly surveys. Gaps indicate months when no survey was conducted.

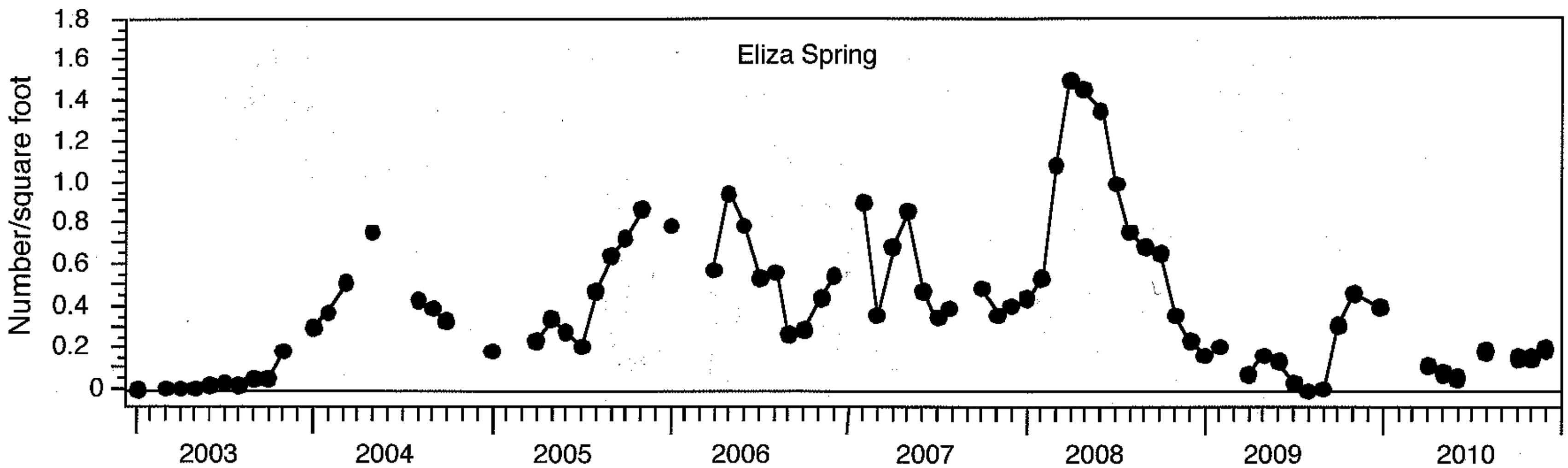

Figure 5.

Effects of Drought in Eliza Spring. Shown below are discharge (DIS) from the Barton Springs complex, dissolved oxygen concentration (DO), and adult (≥1" TL) and juvenile (< 1" TL) *E. sosorum* abundance from 2003 to 2010. Droughts are indicated by the brown bars along the x-axis. Gray horizontal bars indicate lethal concentration thresholds for dissolved oxygen from Woods et al. (2010).

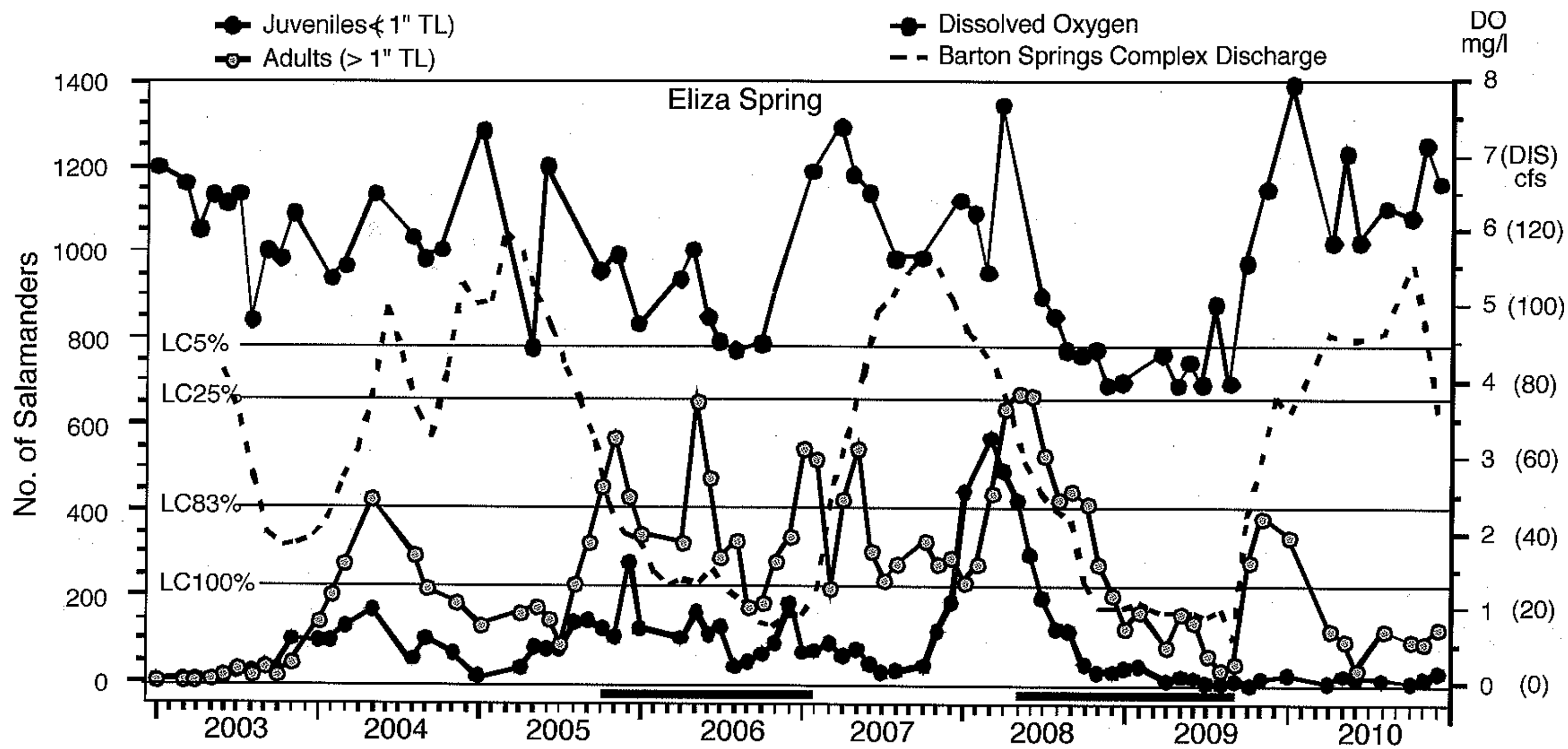

Figure 7.
Percentage of total *E. sosorum* found in each habitat area 1993-2010.

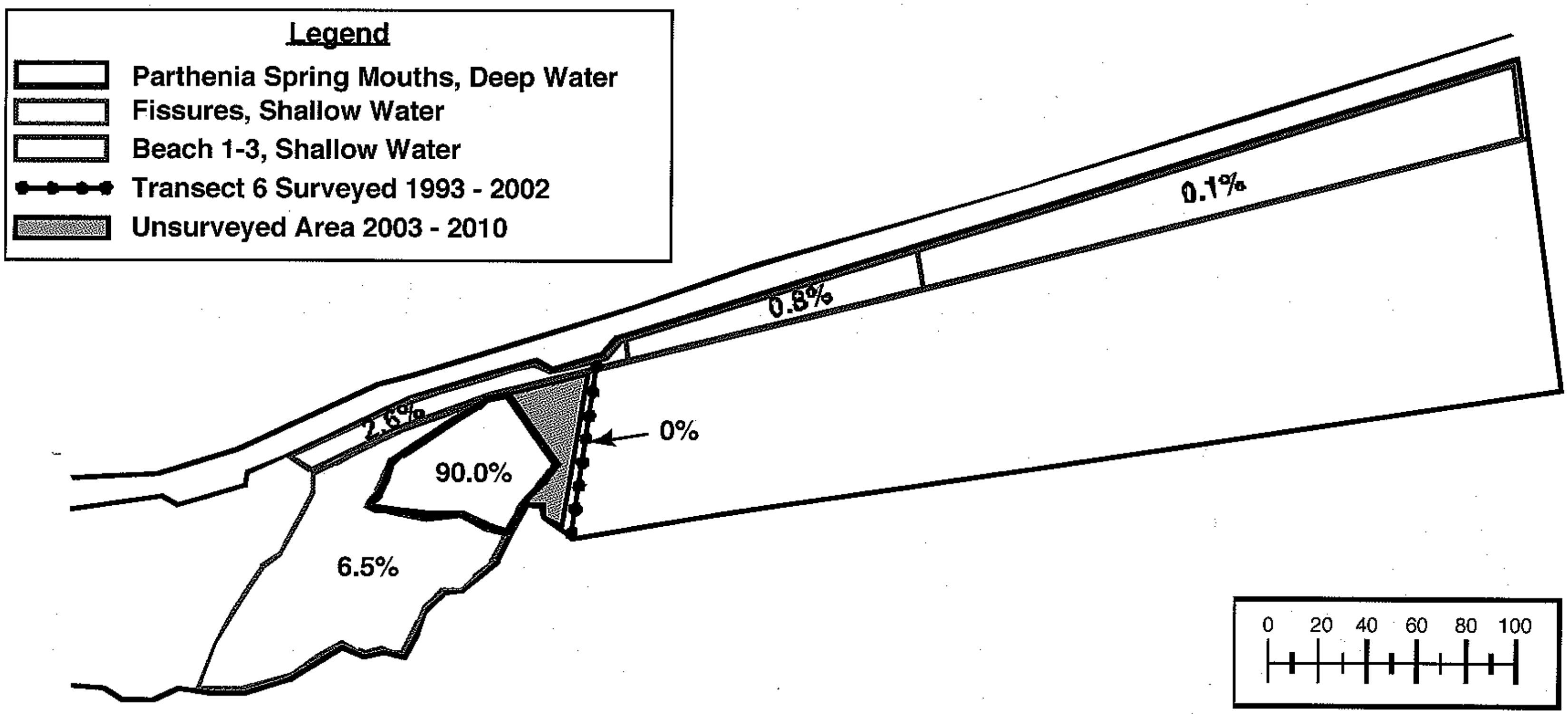

Figure 9.
Abundance of juvenile, young adult, and adult salamanders in Parthenia Spring, and Barton Springs complex discharge (DIS). From 2003 through 2010, salamander abundance increases at this site lag behind discharge increases by approximately six months.

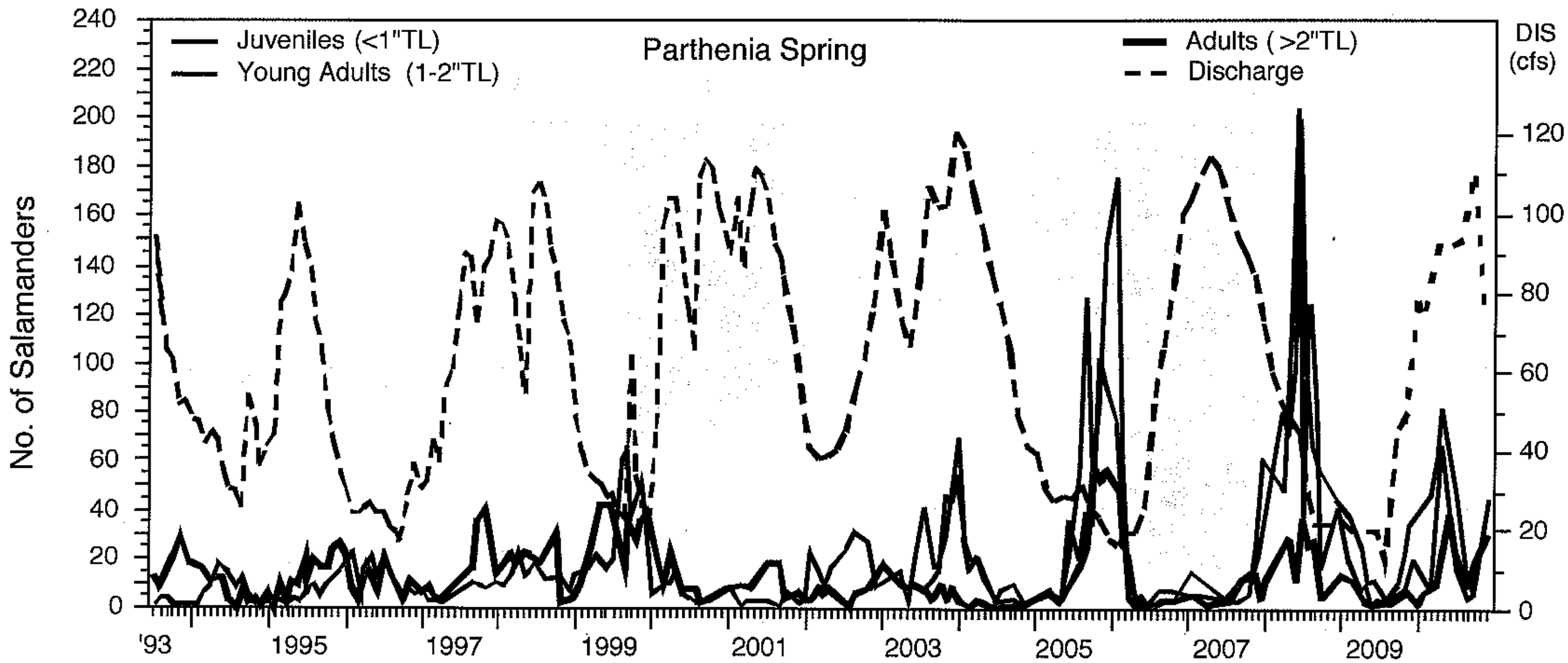

Figure 11.

Salamander Recruitment in Parthenia Spring. Shown are abundances of juvenile, young adult, and adult *E. sosorum* from 2003 through 2010.

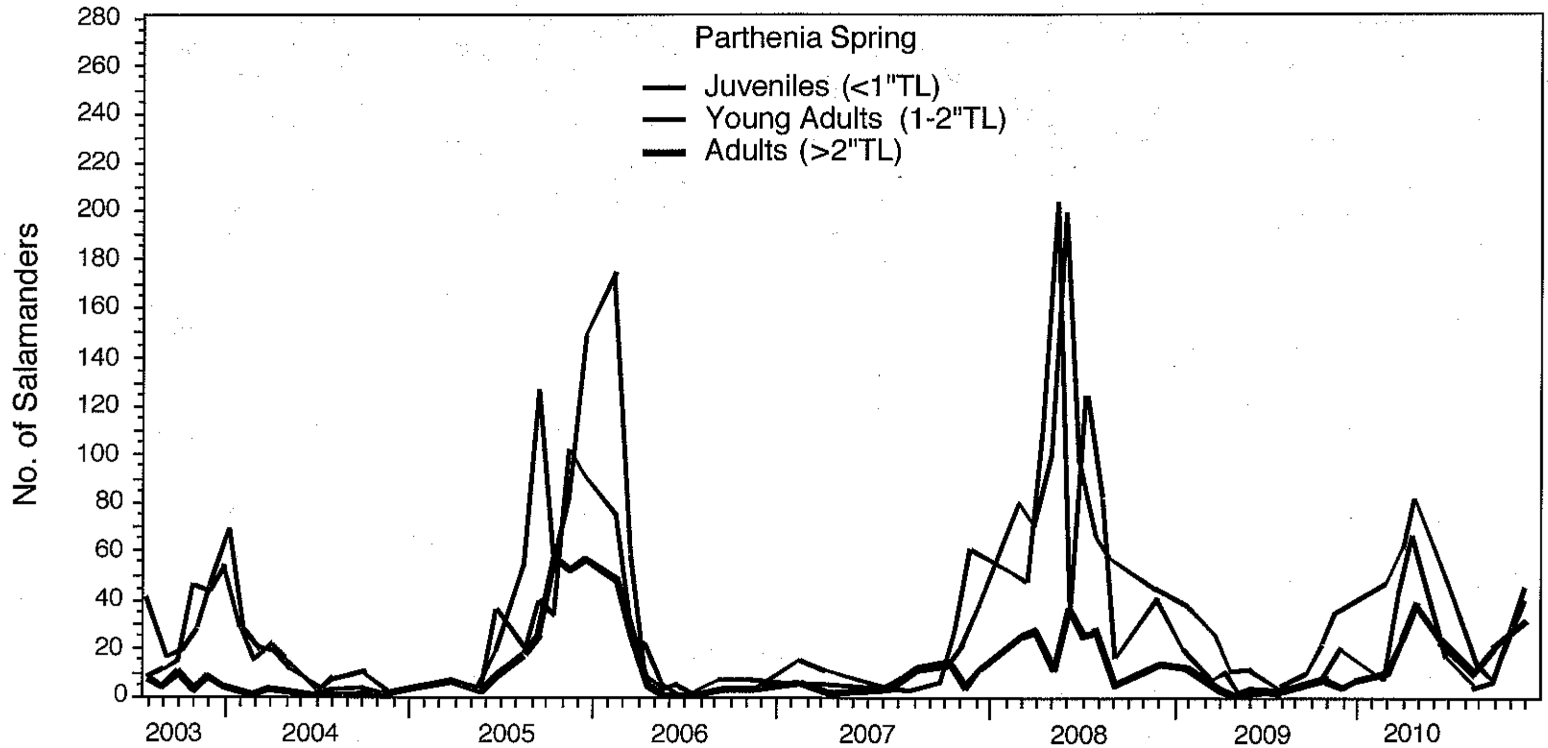

Figure 13.
Eurycea sosorum abundance in Old Mill Spring from 1995 - 2010. Black dots indicate when 0 salamanders were found. Data points from consecutive monthly surveys are connected by lines.

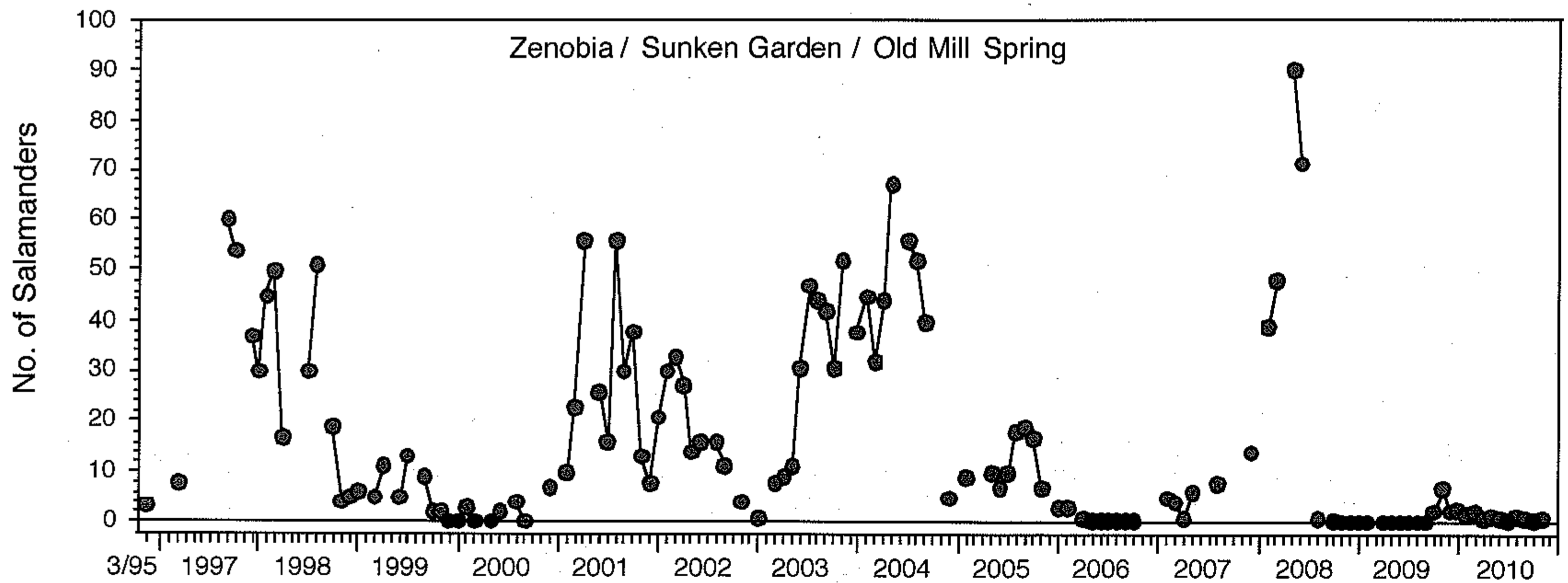

Figure 15.

Effects of Drought in Old Mill Spring. Shown below are discharge (DIS) from the Barton Springs complex, dissolved oxygen concentration (DO), and juvenile (< 1" TL) and adult (≥ 1") *E. sosorum* abundance from 2003 to 2010. Gray filled dots indicate 0 salamanders. Droughts are indicated by the brown bars along the x-axis. Gray horizontal bars indicate lethal concentration thresholds for dissolved oxygen from Woods et al. (2010).

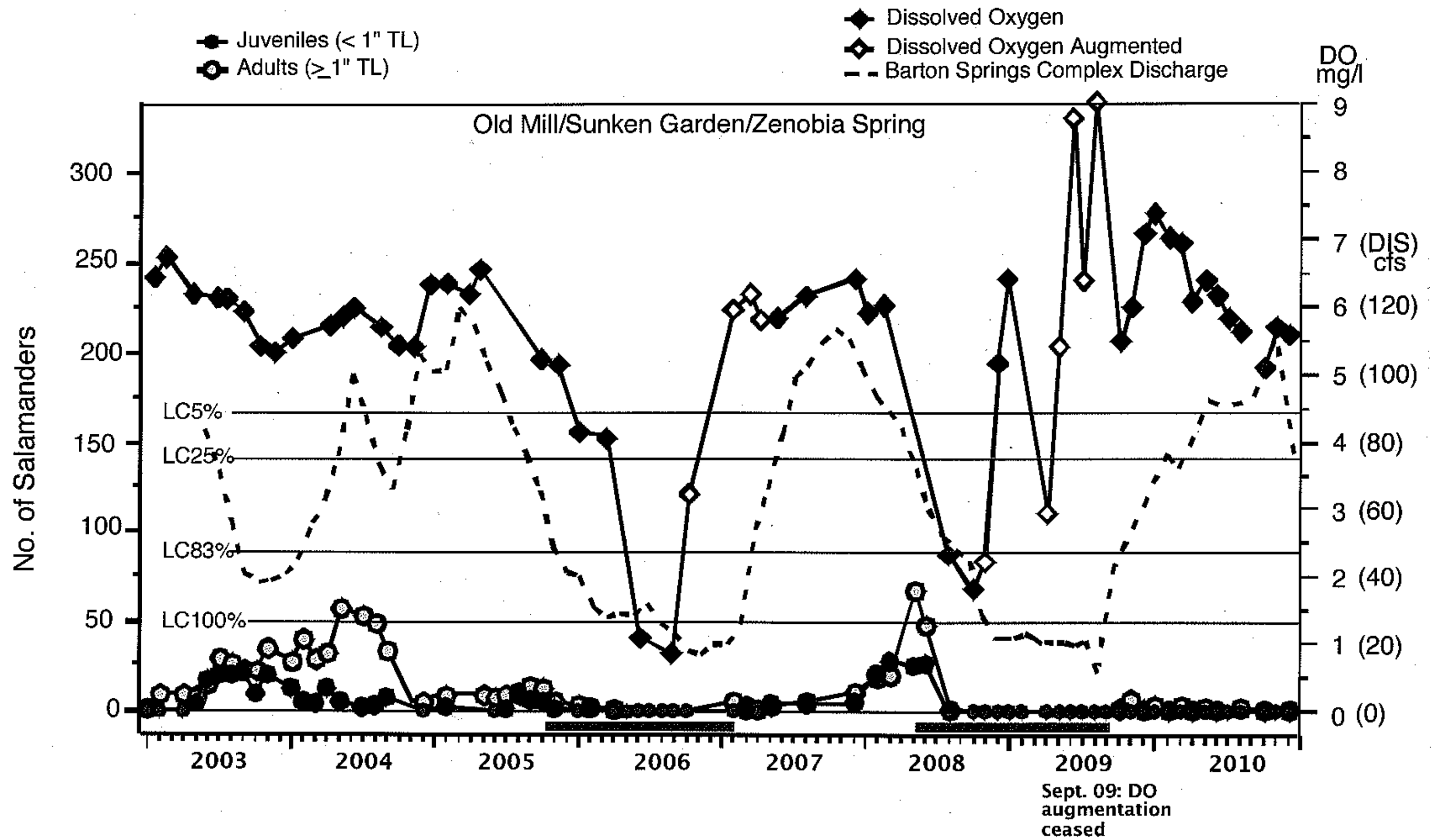

Figure 17a.

a. *Eurycea sosorum* abundance in Upper Barton Spring from 1997 through 2010. Black dots indicate when 0 salamanders were found.

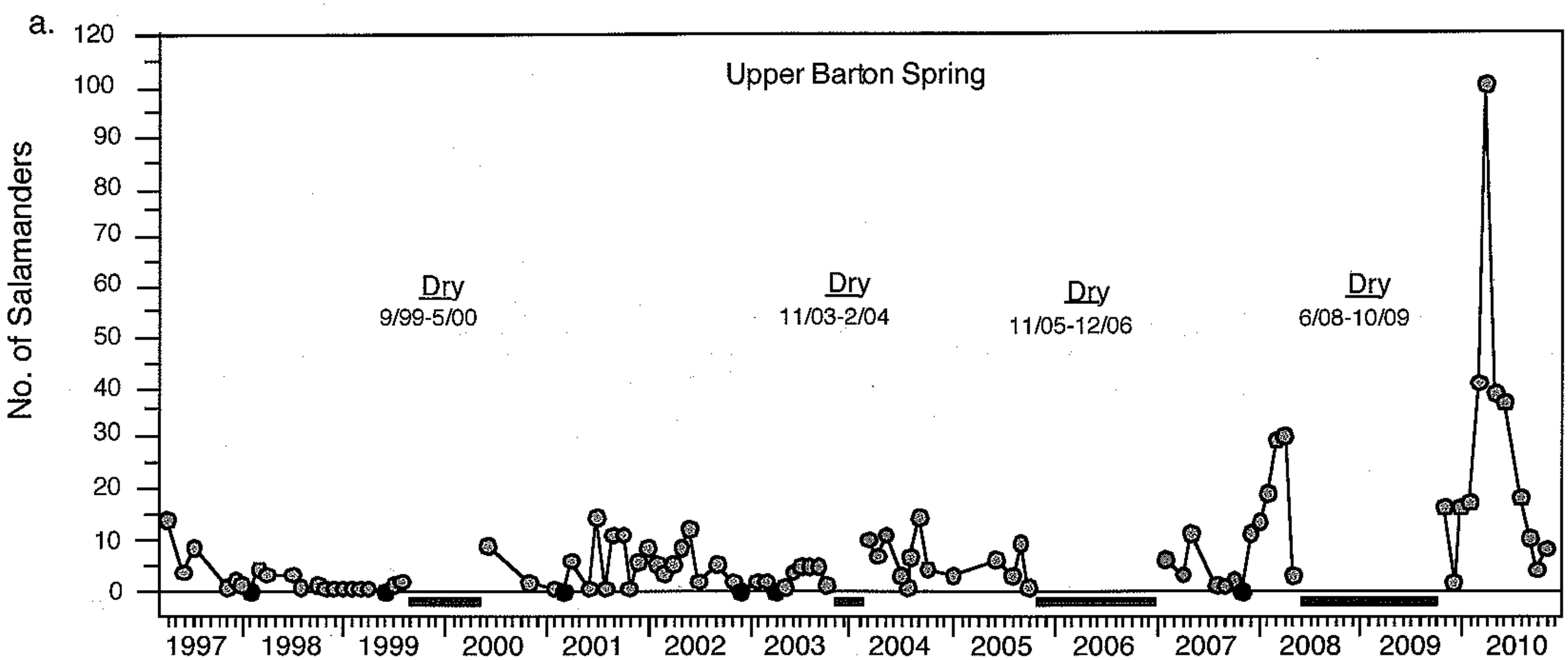

Figure 18.

Abundance of adult (≥ 2" TL), young adult (1-2"TL), and juvenile (≤ 1" TL) *Eurycea sosorum* in Upper Barton Spring from 2003-2010. Each line shows monthly abundance of salamanders of each size class. Periods when there was no water at the surface are listed and denoted by broan bars along the abcissa.