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Primary Research Paper

Ecology of the Jollyville Plateau salamander (*Eurycea tonkawae*: Plethodontidae) with an assessment of the potential effects of urbanization★

Beth Davis Bowles[1,]*, Mark S. Sanders[2] & Robert S. Hansen[3]
[1]*Plant Sciences Graduate Program, Integrative Biology, School of Biological Sciences, University of Texas, Austin, TX 78712, USA*
[2]*City of Austin Water Utility, Balcones Canyonlands Preserve, 3635 Hwy. 620 South, Austin, TX 78738, USA*
[3]*Alan Plummer Associates, Inc., 6300 La Calma, Suite 400, Austin, TX 78752-3825, USA*
(**Author for correspondence: Tel.: (512) 471-4997; Fax: (512) 232-3402; E-mail: beth.davis@mail.utexas.edu*)

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Abstract

The Jollyville Plateau salamander, *Eurycea tonkawae* Chippindale, Price, Wiens, and Hillis, inhabits springs and wet caves of the Jollyville segment of the Edwards Plateau, Texas. The known range of this species is limited to six stream drainages, and most known localities are at risk of impairment from urban development. Our purpose was to gather needed autecological information on *E. tonkawae* and evaluate factors that may affect the distribution and abundance of the species. We conducted visual salamander surveys at nine stream sites across the Jollyville Plateau between December 1996 and December 1998. The survey sites were classified as undeveloped or developed based on watershed impervious cover estimates. We characterized the habitat for each site, including substrate type, discharge, and water quality. Salamander counts varied seasonally, but generally were higher during spring and summer. Salamander densities across sites were positively correlated with rubble and cobble substrate density as preferred cover, and negatively correlated with the standard deviation of water temperature, as expected for a spring-adapted species. In addition, we found that mean salamander densities at sites occurring in undeveloped watersheds were significantly higher than at developed sites, where specific conductance of the water was higher. The results of this study suggest that while habitat and seasonal factors influence surface salamander densities, *E. tonkawae* populations may be most vulnerable to effects associated with urbanization.

Introduction

Urban sprawl has impaired over 50,000 km of streams and rivers in the United States (USEPA, 2000). Impervious cover in watersheds elevates the frequency and intensity of storm flows and reduces baseflow in receiving streams (reviewed in Leopold, 1968; Schueler, 1994: Novotny, 2003) increases erosion and downcutting of the stream channel (Arnold et al., 1982; Booth & Jackson, 1997), and contributes nutrient and toxic pollutant loads (Pitt et al., 1995; Novotny, 2003). The diversity and abundance of benthic invertebrates and fishes are consistently and dramatically lower in urban relative to non-urban catchment streams (reviewed in Paul & Meyer, 2001). The threshold of measurable degradation of stream habitat and loss of biotic integrity consistently occurs with 6–15% impervious cover in contributing watersheds (e.g., Klein, 1979; Schueler, 1994; Booth & Jackson, 1997; Wang et al., 2001; Morse et al., 2003; Roy et al., 2003).

★ This work was conducted while B.D. Bowles and R.S Hansen were employed by the City of Austin Watershed Protection Department Austin Texas.

The karst aquifers of the Edwards Plateau, in central Texas, contribute to thousands of springs (Brune, 1981) that are home to approximately 90 endemic animal species, including subterranean and surface-dwelling invertebrates and salamanders, and several species of fish (Bowles & Arsuffi, 1993). The Jollyville Plateau salamander, *Eurycea tonkawae* Chippindale, Price, Wiens, and Hillis, a perennibranchiate member of the family Plethodontidae, is endemic to springs and caves of the Jollyville segment of the Edwards Plateau. Similar to other populations of *Eurycea*, *E. tonkawae* is restricted to the vicinity of wet caves, springs, and spring-dominated surface flows. Several characteristics of these aquatic habitats have been used to explain the highly localized distribution of perennibranchiate *Eurycea*, including temporal and thermal flow reliability, minimal substrate siltation and calcium carbonate deposition (Tupa & Davis, 1976; Sweet, 1982), and the availability of subsurface refugia and corridors (Dowling, 1956; Rudolph, 1978; Sweet, 1982; Chippindale et al., 1993; Tumlison & Cline, 1997). *Eurycea* salamanders are commonly observed occupying areas under or near rocks, aquatic plants and algae, silt, sand, and organic debris (Tupa & Davis, 1976; Tumlison et al., 1990; Chippindale et al., 1993).

Available information specific to *E. tonkawae* is limited to the systematic description of the species (Chippindale et al., 2000) and anecdotal observations. The known range of this species is limited to six stream drainages, and most known localities are at risk of impairment from urban development due to their small, localized recharge areas (Chippindale et al., 2000). For example, recharge to springs in Bull Creek, which possesses the largest populations of *E. tonkawae*, primarily is from infiltration of rainwater on the plateau and runoff captured by local sinkholes (Johns, 1994). The paucity of ecological and life history information is a hindrance to the development of a watershed management policy that would promote effective protection of the species and its habitat in a region subject to urban expansion. The purpose of this paper is to document the relative abundance of surface-dwelling populations of *E. tonkawae*, identify the existing range of habitat conditions in which the salamanders occur, and provide a preliminary assessment of factors that may regulate the abundance and distribution of the species.

Materials and methods

Study sites

We selected six stream sites for salamander surveys on a monthly or bimonthly basis between December 1996 and December 1998, and two additional sites were surveyed quarterly (Table 1). The selection of sites was based on the consistent

Table 1. Eurycea tonkawae survey sites in Travis County, Texas with estimates of watershed impervious cover

Study Site	Survey frequency	Location	Watershed impervious cover estimate (%)
Spicewood Spring and Tributary (SP)	Monthly or bimonthly	30°21′46″ N, 97°44′51″ W	45
Stillhouse Hollow Spring and Tributary (ST)	Monthly or bimonthly	30°22′18″ N, 97°45′49″ W	22
Barrow Hollow Tributary (BA)	Monthly or bimonthly[1]	30°22′16″ N, 97°46′02″ W	27
Long Hog Hollow Tributary (T3)	Monthly or bimonthly	30°23′49″ N, 97°46′10″ W	16
Tanglewood Spring[2] and Tributary (TA)	Quarterly	30°25′50″ N, 97°46′54″ W	30
Bull Creek Tributary 6 @ Hank's Tract (T6)	Monthly or bimonthly	30°25′30″ N, 97°48′51″ W	15
Bull Creek Tributary 5 @ Hank's Tract[3] (T5)	Monthly or bimonthly	30°25′37″ N, 97°49′04″ W	5
Bull Creek @ Franklin Tract[4] (FR)	Monthly or bimonthly	30°25′08″ N, 97°48′40″ W	3
Wheless Spring and Tributary (WH)	Quarterly	30°27′53″ N, 97°52′25″ W	0

[1]Surveys began July 1998.
[2]Also known as Canyon Vista Spring.
[3]Also known as Bull Creek Spring.
[4]Also known as New Bull Creek Spring.

occurrence of *E. tonkawae* and available access. No random or systematic site selection protocol was attempted due to the limited number of sites available for study. The Barrow Hollow survey site (BA) was added late in the project and therefore was not included in most analyses. All data collection was conducted under approximate baseflow conditions.

Study sites were classified into two groups based on watershed impervious cover estimates (Table 1) grouped here as "developed" (>10%) and "undeveloped" (<10%) following literature threshold values cited above. Impervious cover was estimated from GIS maps of roads and buildings developed using 1997 aerial photos, and an additional 46.45 m^2 was applied to the impervious cover estimates for each building unit to account for driveways and sidewalks (City of Austin, unpubl.). Agricultural activity in these watersheds is minimal, if present at all, and was not detected in the GIS analysis of the aerial photos.

Salamander surveys

We defined the boundaries of the salamander survey areas by the extent of salamander occurrence in the stream reach at the first survey, the practicality of search effort, and representativeness of the habitat type. We divided survey sites into sections based on habitat type: riffle/run (flowing with gravel/cobble substrate), pool (deep or shallow with no flow), bedrock glide (shallow flow with bedrock substrate), or combinations of these types. A minimum of three sections was surveyed at each site and the maximum depth among sections surveyed was approximately 0.3 m. Individuals were assigned to one of two relative size classes based on a visual estimate of total length (tip of snout to tip of tail): large (>2.5 cm) or small juvenile (≤2.5 cm). No consistent attempts were made to determine sex or verify sexual maturity of individual salamanders.

Salamander surveys were conducted at approximately the same day of the month, when possible, and between 9 am and 3 pm. Each survey involved searching the wetted surface of the entire section, including in and under available cover and in the top layer of sediment or detritus. We created stream maps to estimate wetted surface area for each section. The field and survey procedures employed in this project were selected to minimize disturbance to the habitat and avoid direct handling of salamanders. We made no attempt to search for salamanders in subsurface habitats. Numbers of sunfish (*Lepomis* spp.), black bass (*Micropterus* spp.) and crayfish (*Procambarus* sp.) longer than approximately 5 cm encountered during salamander surveys were recorded as potential predators.

Habitat

We recorded habitat observations on the same dates as the salamander surveys, including a visual estimate of the percent of the substrate covered by rocks, algae and plants, leaves, and woody debris. Rock substrates were classified by size based on a modified Wentworth scale (Wentworth, 1922). Percent embeddedness of cobble substrate was a visual estimate of the percent of the rock surface surrounded by carbonate deposits, sediment, sand, or organic detritus. The estimate for each section represents the average embeddedness value for 5–10 rocks. Substrate items were classified as bedrock when they were highly embedded in the substrate and could not be moved with reasonable effort. We estimated flow, or discharge ($m^3\ s^{-1}$), using a Marsh McBirney Model 2000® portable velocity meter following the methodology of Gordon et al. (1992).

On the final sampling date at all sites, we employed a grid design to select 50–100 points in each section to record substrate type and size. Size and type of cover items used by each salamander we encountered also were recorded. We then calculated standardized selection ratios following Manly et al. (1993). Standardized selection ratios represent the probability of use of each cover type by the species based on the number of cover items used and the number available, assuming equal availability of all cover items (Manly et al., 1993).

Water chemistry

We collected surface and spring water samples monthly from all sites on the same date, with the exception of WH where water samples were collected on the same day as each salamander survey. Water temperature (°C), pH, conductivity ($\mu S\ cm^{-1}$) and dissolved oxygen concentration ($mg\ l^{-1}$) were taken at each site with a calibrated Hydrolab® (Hydrolab, Austin, TX, USA). Samples from springs were collected from flowing water as close to the rock orifice as possible. Preservation and chemical analysis methods followed protocols in United States Environmental Protection Agency (1983). Water temperature (°C) also was measured in each section during each survey.

Statistical analysis

We conducted statistical analyses using SYSTAT 10 statistical software (vers. 1.0.0.1) or according to Zar (1984). Analyses were evaluated at 95% confidence and conducted using the section means or site means for each parameter as independent replicates. The section mean for each parameter was calculated by averaging all data collected for that parameter in the section over the 2 year study. Similarly, the site mean for a single parameter was calculated by averaging the site data for that parameter over the 2 year period.

To investigate potential habitat preferences by salamanders, we compared the section mean salamander densities among habitat groups: riffle/run (n = 11), pool (n = 11), and bedrock glide (n = 6) using Kruskal–Wallis non-parametric analysis of variance. Spring pools and sections that contained a combination of habitat types were not included in this analysis.

We used Spearman rank correlation analysis to test the significance of relationships of salamander counts or densities (per m^2 wetted area) versus crayfish counts, substrate cover estimates, substrate embeddedness estimates, water temperature, and flow rates. The sequential Bonferroni procedure described by Rice (1989) was used to assess the significance of the p-values at a table-wide significance level of 0.05.

We conducted t-test two-sample mean comparisons on the site means of salamander densities and selected habitat and water chemistry parameters to determine significant differences between the impervious cover groups. Correlation analysis was rejected for these comparisons because the relationships were nonlinear (Allan, 2004).

Results

Salamander counts

Numbers of *E. tonkawae* we observed at the surface were highly variable among the study sites during the 2 year study (Table 2), primarily due to seasonal fluctuations observed in counts (Fig. 1), and were highest during the spring and summer months. In particular, the number of small juvenile salamanders relative to the total number of salamanders was distinctly higher from March to August in both years (Fig. 1). This pattern was apparent at all sites when viewed individually and in the two sites monitored quarterly (not shown), except where low flows reduced wetted surface area during the summer months. We never observed salamander eggs during the course of this study, but occasionally encountered gravid females (based on observation of eggs through the abdominal wall). Gravid females generally were observed from November through February, however no consistent effort was made to inspect individuals for eggs.

Habitat

Mean salamander densities were significantly higher in riffles/runs and pools than in bedrock glides (H = 9.9, p < 0.01), and mean salamander numbers were positively correlated to the estimated mean area of rubble and cobble by section (Table 3). The standardized selection ratios from the fall/winter 1998 surveys indicate a preference by large *E. tonkawae* for larger rock substrates as cover (Fig. 2). We observed few salamanders under leaves or vegetation relative to the amount of those items available. On the contrary, we found that the probabilities of use of rubble, cobble, and boulder substrates were higher and progressively increased with rock size. The use of leaves as cover may have been minimally underestimated due to the difficulty of locating salamanders in large leaf packs. Additionally, we could not calculate standardized selection ratios

Table 2. Mean (± 1 SD) and range of salamander counts and habitat and water chemistry variables measured at nine *Eurycea tonkawae* sites across all sampling dates. Water chemistry data include spring and surface measurements (n.d. = below detection limit)

Parameter	SP	ST	BA[1]	T3	TA	T6	T5	FR	WH
No. of large	15 ± 9	14 ± 12	7 ± 2	28 ± 24	11 ± 6	20 ± 10	40 ± 21	84 ± 69	37 ± 19
salamanders (>2.5 cm)	(2–38)	(1–41)	(5–9)	(0–92)	(3–19)	(5–41)	(3–76)	(1–280)	(8 – 66)
No. of sm. juvenile	2 ± 4	2 ± 2	0	6 ± 12	1 ± 2	2 ± 3	4 ± 5	11 ± 4	16 ± 26
salamanders (≤2.5 cm)	(0–12)	(0–8)		(0–45)	(0–8)	(0–13)	(0–17)	(0–63)	(0 – 81)
Wetted area (m^2)	50.0 ± 8.8	43.6 ± 10.6	57.1 ± 28.2	195.6 ± 62.0	44.0 ± 2.7	123.9 ± 39.1	117.8 ± 53.3	103.2 ± 7.4	53.2 ± 31.8
	(35.2–58.9)	(30.4–57.3)	(15.0–74.0)	(31.8–246.8)	(38.5–47.4)	(43.2–165.0)	(32.3–246.0)	(13.3–134.0)	(2.3 – 87.9)
Rubble + cobble (m^2)	14.1 ± 3.6	9.3 ± 5.3	8.1 ± 5.4	8.4 ± 3.6	4.3 ± 0.9	10.1 ± 3.5	19.1 ± 7.5	20.3 ± 7.6	7.2 ± 5.5
	(8.2–20.0)	(2.7–18.5)	(2.1–15.2)	(3.2–13.9)	(3.1–6.9)	(6.1–18.0)	(3.1–28.6)	(3.3–36.8)	(0.5 – 16.7)
Flow ($m^3\ s^{-1}$)	0.003 ± 0.003	0.002 ± 0.002	0.004 ± 0.004	0.015 ± 0.018	0.007 ± 0.006	0.039 ± 0.042	0.018 ± 0.015	0.062 ± 0.013	0.007 ± 0.014
	(0–0.010)	(0–0.007)	(0–0.009)	(0–0.070)	(0.001–0.023)	(0–0.134)	(0.002–0.057)	(0–0.238)	(0 – 0.046)
Temperature (°C)	21.9 ± 1.8	18.8 ± 2.8	18.6 ± 3.2	20.2 ± 5.0	21.2 ± 3.5	19.5 ± 3.9	19.6 ± 3.1	18.5 ± 3.0	19.4 ± 2.1
	(19.0–32.0)	(12.2–24.2)	(16.0–25.6)	(10.6–30.0)	(15.0–26.8)	(10.9–27.8)	(14.0–24.9)	(13.0–24.8)	(13.5 – 22.2)
% Embeddedness	12 ± 15	19 ± 17	3 ± 10	13 ± 13	9 ± 12	12 ± 13	16 ± 13	18 ± 15	16 ± 11
	(0–50)	(0–50)	(0–30)	(0–50)	(0–60)	(0–50)	(0–50)	(0–60)	(0 – 40)
Specific conductance	1010 ± 135	991 ± 30	935 ± 25	819 ± 136	846 ± 83	920 ± 40	611 ± 20	556 ± 22	612 ± 32
($\mu S\ cm^{-1}$)	(644–1124)	(863–1120)	(914–967)	(727–1310)	(712–1101)	(850–984)	(575–645)	(523–600)	(567 – 671)
Nitrate–N ($mg\ l^{-1}$)	3.9 ± 0.9	5.5 ± 1.3	5.1 ± 1.2	1.1 ± 0.5	1.9 ± 0.5	0.5 ± 0.2	0.4 ± 0.1	0.1 ± 0.1	0.1 ± 0.02
	(0.6–5.4)	(3.0–8.0)	(2.9–7.9)	(0.3–2.1)	(0.3–2.9)	(0.1–1.0)	(0.1–0.6)	(n.d.–0.4)	(0.03 – 0.1)
Dissolved oxygen ($mg\ l^{-1}$)	7.1 ± 1.0	7.9 ± 0.7	8.2 ± 1.5	10.4 ± 1.6	7.7 ± 1.1	9.5 ± 2.0	7.0 ± 1.4	7.1 ± 1.4	5.6 ± 1.4
	(5.3–9.5)	(7.0–10.0)	(7.1–9.9)	(8.5–13.6)	(5.7–10.4)	(5.7–12.4)	(4.4–9.0)	(4.1–8.9)	(3.1 – 7.3)
pH	6.9 ± 0.4	7.2 ± 0.4	7.8 ± 0.2	7.7 ± 0.4	7.4 ± 0.5	7.5 ± 0.4	7.2 ± 0.4	7.4 ± 0.4	7.3 ± 0.4
	(6.1–8.1)	(6.4–7.9)	(7.4–8.2)	(7.0–8.4)	(6.4–9.3)	(6.6–8.3)	(6.6–8.2)	(6.7–8.3)	(6.4 – 7.9)

[1]Barrow was not included in most study analyses (water quality data collected from March 1997–December 1998).

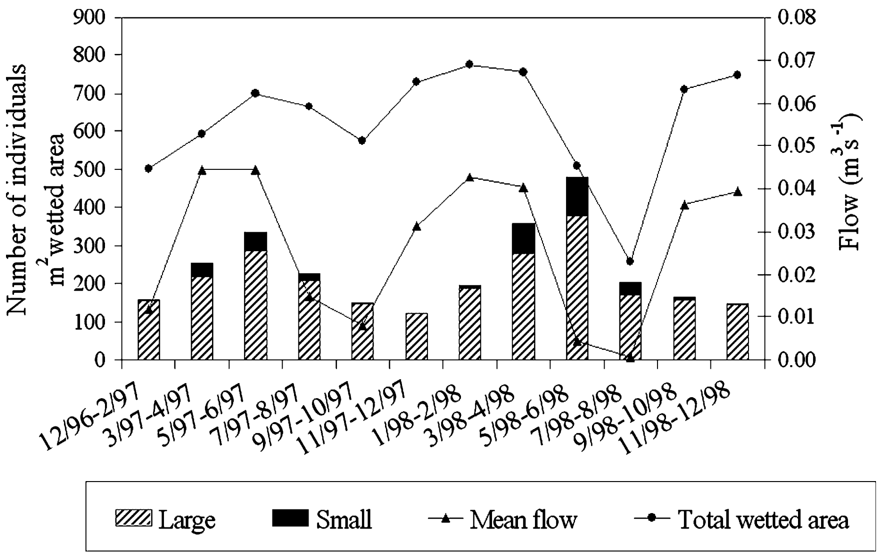

Figure 1. Total *Eurycea tonkawae* counts by size class, mean flow and total wetted area at six sites surveyed between December 1996 and December 1998. The data include sites surveyed at least bimonthly and a mean was used if a site was surveyed both months.

Table 3. Results of the Spearman rank correlation analysis of *Eurycea tonkawae* counts or densities versus selected habitat and water quality variables. All variables are the computed means over the period of the study

Dependent variable	Independent variable	Analysis scale	N	r_s	p	Significant?*
No. of salamanders	Rubble + cobble (m^2)	Section	37	0.74	<0.001	Y
No. of salamanders	no. of crayfish	Section	37	−0.008	>0.1	N
No. of salamanders/m^2	% embeddedness	Section	37	0.17	>0.1	N
No. of salamanders/m^2	Mean temperature (°C)	Section	37	−0.35	<0.05	N
	SD of temperature			−0.45	<0.01	Y
No. of salamanders/m^2	Flow (m^3 s^{-1})	Site	8	−0.071	>0.1	N

* Significance of p was determined following Rice (1989).

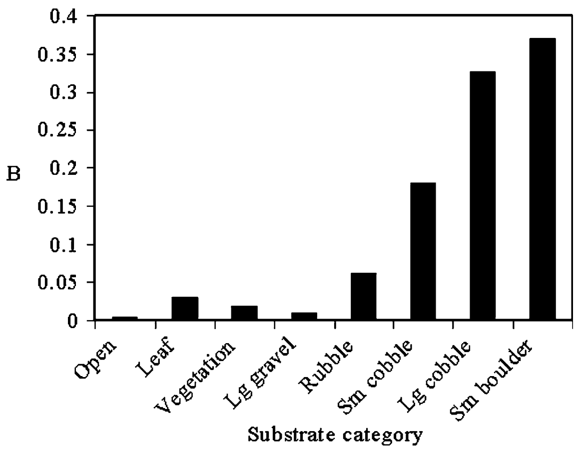

Figure 2. Standardized selection ratios (b) (Manly et al., 1993) representing probability of use by large *Eurycea tonkawae* for available substrate types.

for small juvenile salamanders because of the low number of individuals observed in the fall/winter 1998 survey (n = 2). However, we commonly observed small juvenile salamanders in shallow areas (≤5 cm) near the bank under rubble, small cobble, vegetation, and woody debris over the course of the study.

We did not detect any relationships between salamander densities and embeddedness estimates (Table 3). Rocks were primarily embedded in loose organic detritus or sand and this did not adversely affect salamander presence. Additionally, small substrate particles were rare in glide habitats, which also possessed relatively lower salamander densities.

The maximum and minimum temperatures recorded during this study were 32.0 °C and

10.6 °C (Table 2). Mean salamander densities were negatively associated with standard deviation in water temperature across sections (Table 3), indicating that salamander densities were lowest in sections that were least influenced by springflow.

Baseflow (discharge) rates at the study sites ranged from 0 to 0.238 $m^3 s^{-1}$ (Table 2). Our data suggest that mean salamander densities were not linearly related to mean discharge across sites (Table 3). Rather, we observed that baseflow at these sites affected salamander numbers to the extent that low flows reduced wetted surface area (Fig. 1) or high flows created inhospitable currents in riffles and bedrock glides. For example, when flow rates were high at FR, salamanders were conspicuously absent from riffles with high water velocity. The high water velocity may have scoured available cover and exceeded the capacity of individual salamanders to maintain position in the channel. We were unable to determine if individual salamanders were flushed downstream or retreated to subsurface refugia (e.g., Rudolph, 1978).

Potential predators

We found no significant relationships between salamander abundance and crayfish abundance within or among sites (Table 3). Moreover, we noted few negative interactions between salamanders and crayfish and no increased incidence of missing tails in the presence of crayfish (e.g., Tumlison et al., 1990). In a single instance, we observed a crayfish actively feeding on a salamander held in its cheliped. However, this occurred at the Spicewood site on the same date that other salamanders were observed dead or moribund (cause unknown), suggesting that the crayfish was likely a scavenger and not a predator.

We rarely observed fish in the study areas over the course of the study; consequently no comparison to salamander numbers across sections was conducted. Although direct predation of centrarchid fish on *Eurycea* salamanders has been observed (Tupa & Davis, 1976; Nelson, 1993; R. Hansen, personal observation), *E. tynerensis* apparently reduces fish predation rates relative to other species by retreating into gravel substrate (Rudolph, 1978). We noted that Jollyville Plateau salamanders frequently retreated into the substrate after cover was removed by the surveyors, suggesting they also posses this anti-predation behavior.

Developed vs. undeveloped tributaries

Mean salamander densities were significantly lower in the developed tributaries relative to the undeveloped tributaries (Fig. 3). Our estimates of rubble and cobble substrate, baseflow (discharge) rates and % embeddedness were slightly higher in undeveloped sites, while mean temperature and SD of temperature were lower. However, none of the parameters were significantly different between the impervious cover groupings (Table 4). Three of the developed sites had a relatively higher proportion of bedrock substrate compared to the other sites. The results of the habitat comparisons suggest that this may have contributed to lower densities at those sites.

Mean water specific conductance (μS cm^{-1}) was higher in developed tributaries (Fig. 3) due to increased concentrations of chloride, magnesium, nitrate-nitrogen, potassium, sodium, and sulfate that were present at these sites. Most notably, SH averaged 5.5 mg l^{-1} nitrate-nitrogen (with a max-

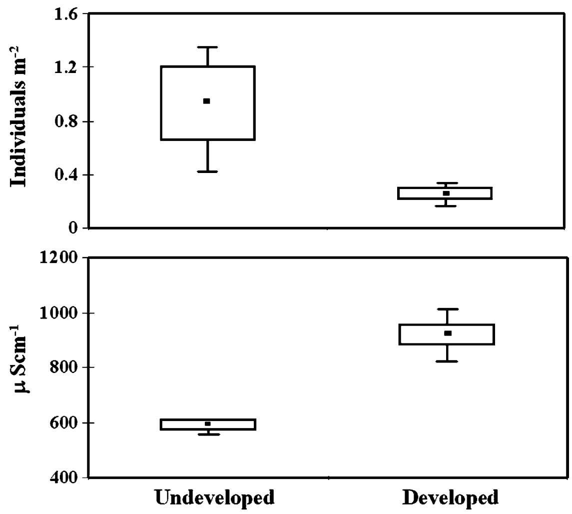

Figure 3. Box and whisker plots of *Eurycea tonkawae* densities and water specific conductance at the undeveloped (n = 3) and developed (n = 5) sites. The boxes represent the mean ± SE. The data point and the whiskers represent the mean and the range, respectively.

imum measurement of 8.0 mg l^{-1}) (Table 2). Because we recorded dissolved oxygen levels at different times of day across sites these values are not directly comparable. Mean pH values were similar between developed and undeveloped tributaries (Table 2).

Discussion

Basic natural history information is necessary to effectively gauge anthropogenic impacts on populations. Unfortunately, such information is frequently lacking or woefully inadequate, particularly for rare species. Our goals in this study were to fill gaps in knowledge of the autecology of *Eurycea tonkawae* and begin to evaluate the impacts of urban development on populations of the species.

Surface abundances of *E. tonkawae* at these sites were higher in the spring and summer months and were not dependent on stream flow rates. While the increase of small juveniles observed during the same time period superficially indicates a seasonal reproduction pattern, the ability of *E. tonkawae* to enter subterranean habitats presently precludes drawing conclusions about seasonal reproduction and survival in these study populations, as well as population size.

We found *E. tonkawae* habitats generally characterized by well-oxygenated water and proximity to springs and seeps, as indicated by the relationship between salamander densities and standard deviation of water temperature. The reliance of perennibranchiate *Eurycea* salamanders on springhead habitats (Sweet, 1982) potentially is due to a minimal capacity for metabolic compensation below the ambient springflow temperature range (McAllister & Fitzpatrick, 1989).

We found a strong relationship between available rock cover and densities of *E. tonkawae*. This is consistent with similar studies on other aquatic salamanders (Davic & Orr, 1987; Parker, 1991; Welsh & Ollivier, 1998; Smith & Grossman, 2003) and explains the relatively low salamander densities in bedrock glides. Additionally, we found that embeddedness of rock substrates did not affect salamander density, likely due to the loose nature of the interstitial particles. Tumlison et al. (1990) noted that *Eurycea tynerensis* densities were highest at sites where embeddedness was near 50% of rock bottom surface, and he hypothesized that the small particles provided spaces for foraging and cover.

Predation risk to populations of *E. tonkawae* at the surface appears to be minimal. We found no sound evidence to suspect crayfish are predators to the salamanders. While anecdotal evidence shows sunfish and black bass are predators, these fish occurred rarely in the salamander habitats.

The impervious cover site groups identified in this study were well-differentiated into those having high salamander densities and low specific conductance (undeveloped), or relatively lower salamander densities and high specific conductance measurements (developed). This likely indicates a mutual response to impacts associated with urbanization. Increased levels of ions in surface water associated with urbanization in Bull Creek and nearby Barton Creek were attributed to wastewater line leaks, roadway runoff, and land use practices such as fertilizer application and irrigation (Johns, 1994; Johns & Pope, 1998).

Table 4. Results of the *t*-test comparisons of mean salamander densities and selected habitat and water quality variables (±1 SE) at *Eurycea tonkawae* sites in undeveloped versus developed watersheds

Parameter	Undeveloped (n = 3)	Developed (n=5)	t	p
No. of salamanders m^{-2}	0.93 ± 0.27	0.26 ± 0.04	3.34	0.016
Rubble + cobble (m^2)	15.5 ± 4.2	9.3 ± 1.6	1.69	0.141
Flow (m^3 s^{-1})	0.029 ± 0.017	0.013 ± 0.007	1.03	0.341
Specific conductance (μS cm^{-1})	593 ± 19	917 ± 38	−6.18	0.001
Mean water temperature (°C)	19.2 ± 0.3	20.3 ± 0.5	−1.48	0.190
SD of water temperature	2.7 ± 0.3	3.4 ± 0.5	−0.88	0.412
% Embeddedness	17 ± 1	13 ± 2	1.64	0.151

Pollutants expected with these sources include toxic hydrocarbons and heavy metals (Novotny, 2003). In addition, the high current velocities associated with elevated discharge in urban watersheds during storm events results in increased instability of substrates (Booth & Jackson, 1997) thereby dislodging and removing cover for salamanders (Orser & Shure, 1972) and potentially exceeding their ability to maintain position in the channel. Other impacts to the populations of *E. tonkawae* we observed at the developed sites in the course of this study further highlight their vulnerability to human activities. Among these are dead salamanders evidently crushed under rocks, and discharges of chlorinated pool water into salamander habitats. Several salamanders were found dead or moribund during the October 1998 survey at SP, but the cause is unknown. In addition, we observed salamanders with spinal scoliosis at ST over the course of the study. We do not know the cause of this deformity, and it merits further investigation to determine if it is a naturally-occurring phenomenon or a product of anthropogenic disturbance (Ryan, 1998).

Amphibians are sensitive indicators of environmental degradation (Barinaga, 1990) and prior research has shown a reduction of salamander densities associated with urban impacts to streams (Orser & Shure, 1972; Willson & Dorcas, 2003). Reduction in habitat quality, due to changes in the natural flow regime and degradation of ground and surface water quality, may be the largest threats from urbanization facing these populations and must be considered in future conservation efforts.

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