Report to the Williamson County Conservation Foundation

Review of Research Literature Related to the Biology, Evolution, and Conservation of Georgetown Salamander, *Eurycea naufragia*

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The Georgetown Salamander

The Georgetown salamander, *Eurycea naufragia*, is a spring and cave-dwelling salamander restricted to the San Gabriel River drainage of Williamson County, Texas. The species is known from only 15 sites occurring along the major tributaries of the upper San Gabriel River (South, Middle, and North forks and Berry Creek; Figure 1). At some of these sites, salamanders have not been observed in recent years and access to all sites is not available. All but two of the known sites are on privately-owned land. The entire range of the species occurs within the immediate vicinity of Georgetown, Texas, an area that is undergoing rapid urbanization (Figure 2), and nearly all known populations are at risk from urban development. The Georgetown salamander has been included as a candidate for listing as an endangered species (US Fish and Wildlife Service, 2001) but is not currently protected by federal or state regulation. Candidate species are given a priority listing by the US Fish and Wildlife Service, which ranges from 1 to 12 and indicates the magnitude and immediacy of threats they face and their taxonomic uniqueness, with higher priority assigned to lower numbers. Largely because of the implementation of the Williamson County Regional Habitat Conservation Plan, the US Fish and Wildlife Service in 2008 reduced the listing priority number of the Georgetown salamander from 2 to 8 (US Fish and Wildlife Service, 2008).

Many amphibians exhibit a biphasic life history pattern, passing through an aquatic larval stage and then metamorphosing to a terrestrial stage. The Georgetown salamander, however, deviates from this basic pattern by exhibiting neoteny, which means that it does

not undergo metamorphosis and retains larval features such as external gills throughout its life. Because of neoteny, Georgetown salamanders are permanently tied to the aquatic environment throughout their entire life.

Figure 1: Location of Georgetown Salamander Populations

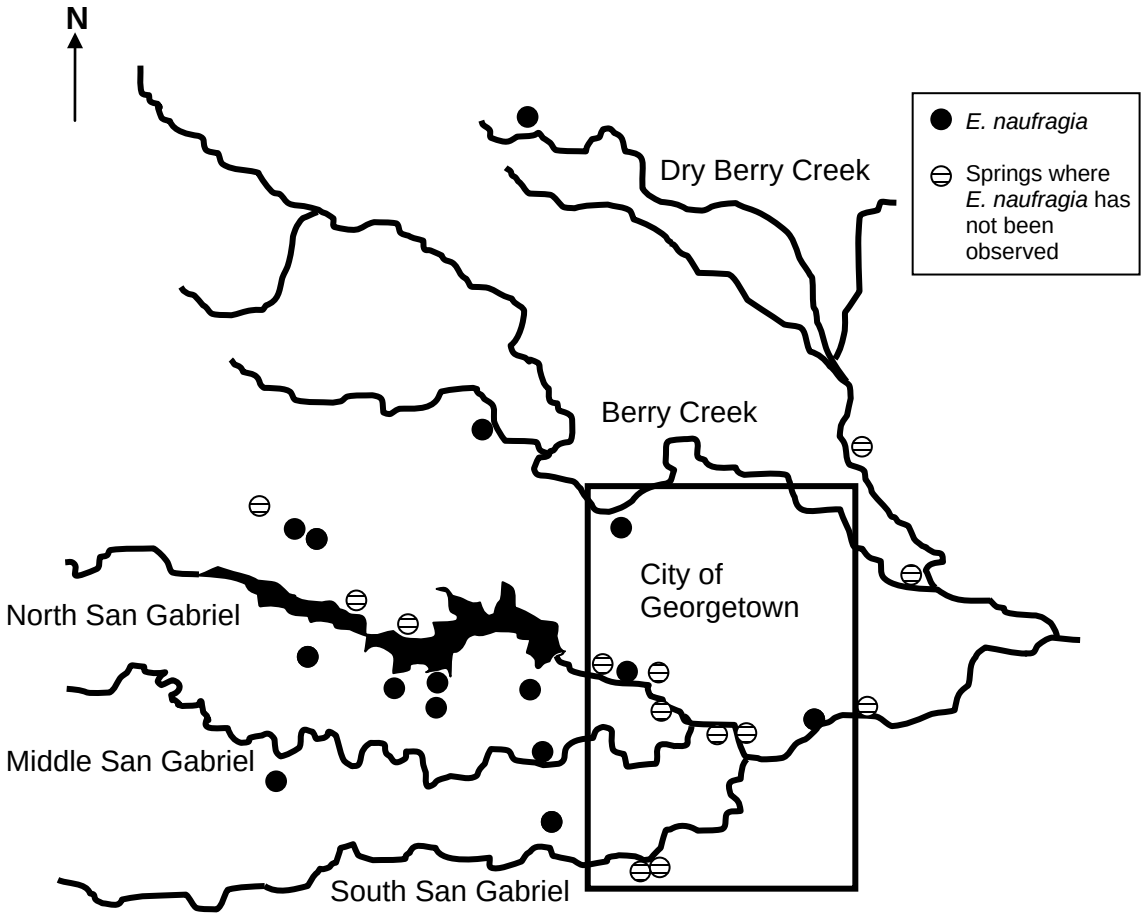
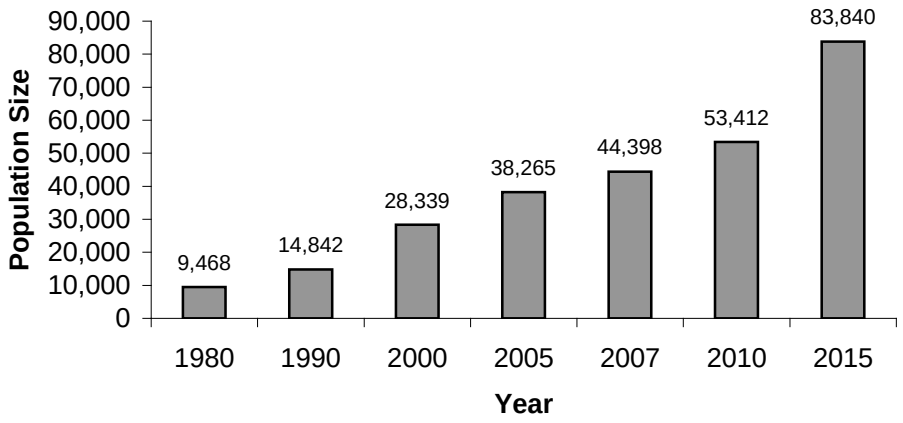


Figure 2: Human Population Growth of Georgetown, Texas, 1980-2015



All known populations of the Georgetown salamander occur in springs or wet caves associated with the Edwards Aquifer (Pierce et al., 2010). Like most salamanders in the genus *Eurycea*, Georgetown salamanders require cool, clear, pristine, flowing water. Increases in groundwater pumping, increases in impervious cover that reduce groundwater recharge, and increased groundwater pollution all threaten the integrity of the aquifer upon which the salamanders depend (Chippindale and Price, 2005). The neotenic life history of the Georgetown salamander and its preference for spring habitats also increases isolation among populations, as animals are unable to migrate overland or for significant distances along surface streams between suitable habitats.

Populations of the Georgetown salamander were originally assigned to the wide-ranging species *E. neotenes* (Bishop and Wright, 1937; Sweet, 1977; 1984) but analysis of molecular data (Chippindale et al., 1993; 1998; 2000; Hillis et al., 2001) demonstrated the presence of numerous evolutionarily distinct lineages within central Texas *Eurycea.* Chippindale et al. (2000) found that populations north of the Colorado River were

monophyletic (derived from a single ancestor) and exhibited considerable genetic divergence from other central Texas *Eurycea*. Based on analysis of proteins, mitochondrial DNA sequences, morphology, and osteology, Chippindale et al. (2000) described three species north of the Colorado River: *E. tonkawae* from the Jollyville Plateau in Travis Co. and Williamson Co., Texas; *E. naufragia* from the San Gabriel River drainage in Williamson, Co., Texas; and *E. chisholmensis* from Salado Creek, Bell Co., Texas. Chippindale et al. (2000) listed seven known populations of *E. naufragia*. They suggested that additional populations might occur west of Georgetown.

Little is known about the biology of the Georgetown salamander. Indeed, only two published scientific papers focus specifically on the species: the original description of the species by Chippindale et al. (2000) and a paper by Pierce et al. (2010) providing monthly surface counts at one site and microhabitat preferences of salamanders at two sites. There are no data on reproduction, survival, growth rates, physiology, diet, or behavior. The species' precise geographic distribution is unknown; it likely occurs at additional spring and cave sites—indeed two new localities were discovered in just the past year (Pierce, personal observation).

The extremely limited nature of research on the Georgetown salamander makes development of conservation and management plans for the species difficult. Nevertheless, research conducted on other spring- and stream-dwelling salamanders provides insight into environmental and biological factors that potentially impact populations the Georgetown salamanders. Knowledge of what has been learned about

the ecology and conservation biology of these other species can help fill the gap in our current knowledge of the Georgetown salamander until more research has been conducted on the species.

Evolution of the Genus *Eurycea*

Salamanders of the genus *Eurycea*, commonly known as brook salamanders, are a diverse group of plethodontid salamanders found in the eastern half of North America. As their name implies, many of the species occur in clear, fast-moving streams, most often in eastern deciduous forests of the United States (Petranka, 1998). This group of salamanders belongs to the family Plethodontidae, which is characterized by an absence of lungs and is the largest family of salamanders.

Kozak et al. (2009) combined DNA sequence data from three mitochondrial genes and two nuclear genes to create a comprehensive phylogeny of North American plethodontid salamanders. They demonstrated that *Eurycea* belongs to one of three subgroups (subfamily Spelerpinae) and is most closely related to salamanders in *Pseudotriton*, *Gyrinophilus*, and *Sterochilus*.

The molecular analysis conducted by Kozak et al. (2009) revealed four major clades (evolutionary lines) within the genus *Eurycea*.

Clade A – This group consists of three species (*E. multiplicata*, *E. spelaeus*, and *E. tynerensis*) that occur in the Ozark Highlands.

Clade B – This group consists of at least 13 species found on the Edwards Plateau of central Texas, plus *E. quadridigitata* from Mississippi.

Clade C – This group consists of *E. longicauda*, *E. lucifuga*, and *E. guttolineata*, three species that are widely distributed in eastern and midwestern North America.

Clade D – This group consists of the *E. bislineata* species complex, which is made up of *E. aquatica*, *E. bislineata*, *E. cirrigera*, *E. junaluska*, and *E. wilderae*, as well as several undescribed species. Recent analysis of mitochondrial DNA sequences within this clade (Kozak et al., 2006) indicates that *E. aquatica*, *E. bislineata*, *and E. junaluska* are each monophyletic and probably represent distinct species. However, *E. cirrigera* and *E. wilderae* are composed of a number of distinct lineages, whose genetic affinities do not correspond well with their currently assigned species names.

The subfamily Spelerpinae, which includes *Eurycea*, has its highest species richness in the southern Appalachians, suggesting an initial origin and radiation in this region. After a long residency there, the group probably spread throughout eastern North America and into the Ozark Highlands and central Texas.

Clade B includes those species of *Eurycea* found on the Edwards Plateau of Texas and *E. quadridigitata* from the Gulf coast plain. The close relationship of the central Texas *Eurycea* to *E. quadridigitata* suggests that salamanders from the southeast colonized the

Edwards Plateau. This group currently consists of at least 13 named species with additional unnamed species likely.

Environmental Factors Potentially Affecting the Georgetown Salamander

Although little is known specifically about the ecology of the Georgetown salamander, considerable research has been conducted on other salamanders that occur in similar types of habitats—specifically salamanders that occupy wet caves, surface springs, and streams. The results of this research provide insight into factors that potentially affect the Georgetown salamander and can help guide conservation planning until more research has been conducted on the Georgetown salamander itself.

Urbanization

Urban land use has a number of potential impacts on streams and springs, including effects on the flow regime, changes to the stream channel, addition of sediments, effects on water chemistry, and changes in the biological communities found there. A number of studies demonstrate that increased urbanization negatively impacts stream and spring salamanders. One of these studies examined the effect of urbanization on the Jollyville Plateau salamander (*Eurycea tonkawae*), a species that is closely related to the Georgetown salamander and occurs in similar habitat. Bowles et al. (2006) studied populations of the Jollyville Plateau salamander in central Texas and found that salamander densities were higher at sites occurring within undeveloped watersheds compared with sites in developed watersheds. These researchers found higher conductivity of spring water at salamander sites in developed watersheds, which they

attributed to use of fertilizer and irrigation factors associated with urbanization. Their research suggested that lower salamander densities in developed watersheds were the result of degraded water quality in the springs.

Similarly, Willson and Dorcas (2003) examined the association of stream-dwelling salamanders *E. cirrigera* and *Desmognathus fuscus* and watershed disturbance due to urbanization. They found no association between relative abundance of salamanders and percent of disturbed habitat within 10.7, 30.5, and 61.0 m buffer zones surrounding salamander study sites. However, they did find fewer salamanders in watersheds that had more disturbed habitats than in watersheds with less undisturbed habitats. They concluded that urbanization was important in determining salamander abundance, but that the buffer zones they examined were not sufficiently large to account for the watershed-scale effects of the disturbance. It is important to note that many stream salamanders, such as those studied by Willson and Dorcus (2003), include both aquatic and terrestrial life history phases. For these species, the scale (such as buffer size) and nature of landscape effects will be influenced by parameters affecting both the terrestrial and aquatic phases. For completely aquatic salamanders such as the Georgetown salamander, changes to the terrestrial environment may still impact salamander populations through effects on water quantity and quality, but the scale and nature of these effects may be different from those observed with species that have biphasic life histories.

Orser and Shure also (1972) found a strong inverse correlation between densities of the stream salamander *D. fuscus* and urban influence. They examined five sites with a range of urban disturbance, defined by proximity of homes and paved roads, presence of runoff ditches or drainage culverts, evidence of sand deposition, and abundance of natural vegetation. Salamanders were absent from the most severely disturbed sites and densities were lower at other disturbed sites. The site with the least disturbance showed the highest salamander density.

Among 43 streams in North Carolina, Miller et al. (2007) observed lower abundance of larval *E. cirrigera* in streams with more impervious cover in the upstream catchment areas. They attributed the negative effects of urbanization on salamander abundance to increased peak flows, increased sedimentation, reduced base flow, and water quality changes associated with impervious cover.

Barrett et al. (2010) observed that density of two-lined salamanders (*E. cirrigera*) declined between hatching and metamorphosis, and the decline was more pronounced in urban and developing streams (89% and 98% decrease respectively) than in pasture and forest streams (74% and 70% decrease respectively). Their analysis provided insight into the mechanism of this decline; they showed that this effect of urbanization was associated with increased impervious cover and increased water flow during storm events. Furthermore, by testing larval salamanders in artificial streams, they were able to confirm that larvae on sand-based substrates common to urban streams were flushed downstream at lower water velocities than larvae on rock and cobble substrates common

to forest streams. They concluded that the negative effects of urbanization on stream salamanders was due to increased water velocity associated with impervious cover and altered stream substrates.

Price et al. (2006) examined the relationship of salamander abundance to land use changes in North Carolina. They found that from 1972 to 2000 populations of the southern two-lined salamander (*E. cirrigera*) decreased 32% to 44% and populations of the northern dusky salamanders (*D. fuscus*) decreased 21% to 30%. Their analysis suggested that these decreases in stream salamanders were the result of widespread conversion of forest land to urban development in small catchment areas. These species have both aquatic and terrestrial phases, and so the declines they observed may be due to landscape changes that affect the terrestrial phases, the aquatic phases, or both.

Similarly, Grant et al. (2009) found that three (*E. bislineata, D. fuscus, Pseudotriton ruber*, and *E. cirrigera*) out of four stream-dwelling salamanders had lower occupancy in urbanized areas than undeveloped areas.

In addition, Corn et al. (2003) and Chippindale and Price (2005) concluded that the health and survival of salamanders on the Edwards Plateau in Texas were threatened by increasing urbanization. All species in this group are neotenic and occur in springs and wet caves. Most have highly restricted distributions. They are all dependent on the quantity and quality of water in the Edwards Aquifer, which feeds the springs upon which the salamanders depend. Rapid urban growth in the Austin and San Antonio

metropolitan areas has resulted in increased pumping of groundwater and lowered levels of the aquifer and declines in spring flows (Chippindale and Price, 2005).

These studies indicate that increased urbanization negatively impacts spring and stream salamanders. Evidence suggests that the negative impacts of urbanization occur primarily through changes in water quality and water flow. Water quality in urbanized watersheds may be impaired by runoff of fertilizer, pesticides, herbicides, oil, and other contaminants that enter streams and aquifers. Indeed, Bowles et al. (2006) found increased conductivity and nitrogen/nitrate concentration in the springs of developed watersheds where salamanders were less abundant. Willson and Dorcas (2003) also found increased conductivity in more disturbed watersheds with lower salamander abundance. Increased conductivity, which is a measure of the electrical conductance of the water, is not necessarily a threat to aquatic life, but increasing conductivity often reflects the input of pollutants to the watershed, which is likely to be detrimental to salamanders.

Urbanization also potentially alters water flow in springs and streams where salamanders reside. Increases in impervious cover in urbanized watersheds cause more rapid storm runoff, so that flow at urbanized sites is often more variable. Orser and Shure (1972) concluded that urbanization negatively impacts stream salamanders largely through changes in velocity and volume of water flow, and research indicates that optimal flow regimes are critical for many stream and spring salamanders (see below). Large volumes of water in more urbanized streams during storm events may create instability of the

stream substrate and directly disrupt salamanders. In addition, flash flooding and altered flow at urbanized sites may degrade salamander habitat by increasing erosion and sedimentation, which fills the interstitial spaces within the stream-bed substrate. These interstitial spaces are important for many stream dwelling salamanders (see below).

Roads

A factor often associated with urbanization is the construction and presence of roads. Roads potentially affect salamanders in several ways. Road construction and maintenance may lead to increases in stream sediment, which negatively impacts many salamander populations. Roads increase impervious cover, leading to greater variation in stream velocity and the potential input of pollutants into stream and spring water.

Unfortunately, the number of studies looking at the effect of roads on stream salamanders is limited. Ward et al. (2008) examined the effects of road crossings and other environmental factors on richness, diversity, and abundance of stream-dwelling salamander communities in the Appalachian mountains of West Virginia. They found that roads affected salamander richness and diversity, but the effects were species specific. Some species were negatively impacted by roads, while other, more disturbance-tolerant species, actually benefited from the presence of roads.

Welsh and Ollivier (1998) examined the effect of road construction in California's redwood forests on the densities of two stream-dwelling salamanders, the Pacific giant salamander (*Dicamptodon tenebrosus*) and the southern torrent salamander (*Rhyacotriton*

variegates), as well as on tailed frogs (*Ascaphus truei*). In their study area, the construction of a highway resulted in a large, accidental infusion of fine sediment into pristine streams during a 1989 storm event. The researchers found that the densities of both salamander species were lower in streams with more sediment, but the nature of the effect differed between the two species. They concluded that that the Pacific giant salamander was less sensitive to fine sediments than the southern torrent salamander, but was negatively associated with sand. Welsh and Ollivier (1998) suggested that the species they studied were all vulnerable to sedimentation because of their common use of interstitial spaces in the streambed substrate.

Timber Harvest

A number of studies indicate that timber harvest negatively impacts stream salamanders (reviewed in Corn et al., 2003). Timber harvest negatively affects salamander abundance by removing stream-side or canopy vegetation, creating barriers to dispersal by terrestrial adults, and increasing fine sediments within the stream. Lowe and Bolger (2002) found that spring salamander (*Gyrinophilus porphyriticus*) abundance in New Hampshire headwater streams increased with increased time since timber harvest and they concluded the negative effects of timber harvest were largely due to an increase of fine sediments into the streams. Corn and Bury (1989) found that species richness, density, and biomass of three species of stream-dwelling salamanders in Oregon were higher in streams flowing through uncut forests than streams flowing through cut forests. They also attributed the negative effects of timber harvest to increased sedimentation in the streams.

Rocks and Other Cover Objects

Many species of stream-dwelling salamanders occupy cover objects in the aquatic environment, most likely to avoid predation, and several studies have shown that the presence of large rocks and cobble are positively associated with abundance of spring and stream-dwelling salamanders. Pierce et al. (2010) found that Georgetown salamanders preferentially utilized larger rocks for cover objects and larger salamanders used larger rocks. Willson and Dorcas (2003) found that highly disturbed stream sites in urbanized watersheds, which had lower salamander densities, were characterized by low amounts of cover on the streambed. Orser and Shure (1972) found that density of *Desmognathus fuscus* was positively associated with availability of cover objects within the stream.

Some evidence suggests that salamanders prefer rocks over other potential cover objects. For example, Pierce et al. (2010) found that Georgetown salamanders utilized a higher proportion of rocks as cover objects than sticks, leaves, and other objects. Bowles et al. (2006) found limited occupation of leaves and vegetation by the Jollyville Plateau salamander, although this may have been due to the difficulty of finding salamanders in habitats dominated by these types of cover objects.

In addition to providing cover, large size substrates also provide a greater abundance of interstitial spaces, which appear to be important for many species of salamanders (see next section). Davic and Orr (1987) found that that the densities of several salamanders (*D. quadramaculatus*, *Eurycea bislineata*, and *Gyrinophilus porphyriticus*) were positively associated with density of pebbles and cobbles in the stream bed. This effect

was probably due to the protection from predators that pebbles and cobbles provided the salamanders, as well as increased surface area that allowed colonization by benthic macroinvertebrates. Similarly, Stoddard and Hayes (2005) found that *Dicamptodon tenebrosus* and *Rhyacotriton* spp. were negatively associated with proportion of small substrates within streams. Bowles et al. (2006) found that the density of Jollyville Plateau salamanders was positively correlated with rubble and cobble substrate density.

Bonett and Chippindale (2006) found that neotenic populations of *E. tynerensis* were associated with the presence of chert, a very hard sedimentary rock made of quartz. The chert substrate provided numerous interstitial spaces in stream substrate that salamanders utilized. In streams dominated by chert, neotenic salamanders were able to move through interstitial spaces to access subsurface water during dry months, when surface water disappeared. In areas dominated by more finely sorted substrate lacking in interstitial spaces, neotenic salamanders were not able to survive and the populations consisted of salamanders that underwent metamorphosis. Thus, the presence or absence of interstitial spaces appeared to control the life history patterns of local populations.

Sand, Silt, and Sediment

Interstitial spaces within the streambed substrate appear to be an important habitat requirement for many stream-dwelling salamanders, and this is particularly the case for spring and stream-dwelling *Eurycea*. Interstitial spaces provide refugia from predators and increased surface area for macroinvertebrates, upon which the salamanders feed. Because of the importance of interstitial spaces, sand, silt, and other types of fine

sediment that fill these spaces usually have negative impacts on the salamanders. Bonett and Chippindale (2006) found that streams with sand, silt, and poorly sorted substrate materials supported fewer populations of neotenic *E. tynerensis*. In areas with substrates that lacked interstitial spaces, salamanders were forced to metamorphose and neoteny was less common. Tumlison et al. (1990) similarly found that substrate size was the best indicator of E. *tynerensis* habitat and that embeddedness (the degree to which fine sediments surround coarse substrates) was negatively associated with salamander density.

Welsh and Ollivier (1998) concluded that stream-dwelling salamanders in the Northwest (*Dicamptodon tenebrosus* and *Rhyacotriton variegates*) were positively associated with presence of coarse substrate (cobble). Road construction in their study site increased sand and other fine sediment within the stream, negatively affecting salamander density. Orser and Shure (1972) observed that salamander densities were negatively related to the amount of suspended particle material in stream water and that urbanization within the stream watershed increased soil erosion and sedimentation.

Stream Gradient

Stream gradient (how much the stream bed drops in elevation over a given distance) is a characteristic that often plays an important role in structuring stream communities. Stream gradient has a large effect on water velocity and sedimentation, factors with known effects on stream salamanders. Gradient also potentially affects oxygen levels and water temperature. In their study of Appalachian mountain salamanders, Ward et al. (2008) found higher salamander abundance in higher-gradient streams. They attributed

this effect to the fact that lower gradient streams were more likely to accumulate fine sediments and that salamander abundance was negatively associated with fine sediments. Similarly, Corn and Bury (1989) found that densities of Pacific giant salamanders (*Dicamptodon ensatus*) and Olympic salamanders (*Rhyacotriton olymoicus*) were positively correlated with gradient in streams passing through logged forests in Oregon but not in streams passing through unlogged forests. They proposed that sedimentation caused by logging was detrimental to the salamanders, but this sedimentation was less likely to accumulate in streams with higher gradient. Wilkins and Peterson (2000) also found a positive association between channel gradient and habitat occupancy by the Columbian torrent salamander, *R. kezeri*.

Predators

Predators potentially influence aquatic salamander communities through both direct and indirect effects. Potential predators of stream-dwelling salamanders include fish, snakes, birds, and large invertebrates, such as crayfish. A number of studies indicate that fish are predators on stream salamanders. Bowles et al. (2006) and City of Austin (2001) concluded that centrarchid fish are predators on *Eurycea tonkawae*, and City of Austin (2001) found a negative correlation between salamander numbers and presence of centrarchid fish at one site; others have directly observed predation by fish on *E. tonkawae* (Nathan Bendik, personal communication).

Rudolph (1978) studied five species of salamanders that inhabited springs and spring-fed creeks in the Central Highlands of Oklahoma, Arkansas, and Missouri. He noted that

salamanders were rarely abundant at sites where a well-developed fish fauna occurred. The one exception was *E. tynerensis*, which often co-occurred with fish. In the laboratory, predatory fish consumed all five species, although there were differences in levels of predation among salamander species (*E. tynerensis* was the most resistant to predation).

Epp and Gabor (2008) observed predatory fish (large-mouth bass and red breast sunfish) feeding on the San Marcos salamanders (*E. nana*) in the field and demonstrated that these fish will consume *E. nana* in the laboratory. They showed that *E. nana* significantly lowered its activity when exposed to chemical cues from both native and nonnative predatory fish, suggesting that these salamanders (which are closely related to the Georgetown salamander) have evolved behaviors to avoid predatory fish. Other studies, however, indicate that *E. sosorum* (another closely related species) exhibits weaker antipredator behavior to olfactory cues, with some individuals exhibiting ineffective antipredator behavior in the face of visual and olfactory cues from fish predators (Hayley Gillespie, unpublished observations). Thus, antipredator behavior may vary even among closely related species. Stream salamanders can also avoid predatory fish by occupying habitats that are unsuitable for fish and utilizing microenvironments—such as interstitial spaces and cover objects—where they are protected from fish predation.

Lowe and Bolger (2002) observed that spring salamanders (*Gyrinophilus porphyriticus*) were less abundant in New Hampshire headwater streams where brook trout were present, although it was not clear whether this was a result of predation or competition.

Crayfish are potential predators on salamanders. Two studies found no association between salamander abundance and crayfish in Texas *Eurycea* (Bowles et al., 2006; Pierce et al., 2010), but others have observed crayfish predation on salamanders (Nathan Bendik, personal communication).

Invertebrate Abundance

All salamanders are carnivorous, and stream salamanders typically feed on aquatic macroinvertebrates. Using fecal analysis, Rudolph (1978) examined the diet of five species of spring- and stream-dwelling *Eurycea* salamanders and found that common prey items included ostracods, copepods, isopods, amphipods, mayfly nymphs, dipteran larvae, molluscs, and caddis fly nymphs.

Given that stream salamanders feed on aquatic invertebrates, one might expect to see a positive relationship between salamander density and invertebrate abundance in the same habitat. Indeed, several studies have detected a positive relationship between number and abundance of invertebrates and abundance of salamanders. For example, Willson and Dorcas (2003) found a positive association between number of invertebrate taxa and numbers of two species of stream salamanders, *Desmognathus fuscus* and *E. cirrigera*. However, City of Austin (2001) found no relationship between presence of benthic invertebrates and density of *E. tonkawae*. Similarly, Orser and Shure (1972) found no association between invertebrate density and salamander densities in *D. fuscus*. The absence of an association in these latter studies may reflect the fact that salamanders are selective in their prey and the studies looked only at the relationship between salamander abundance and the density of all invertebrates. It is also important to note

that even when an association between salamander abundance and invertebrate abundance is demonstrated, the increased number of salamanders may not be due to increased food supply, but may merely reflect that fact that salamanders and invertebrates are sensitive to the same water and habitat parameters.

Water Velocity and Discharge

Water velocity and discharge appear to be critical habitat parameters for many stream and spring salamanders. For example, Bowles et al. (2006) found that low flows reduced wetted surface areas, thereby reducing densities of the Jollyville Plateau salamander, but high flows created inhospitable currents. Optimal water velocity probably varies by species. Habitat features associated with velocity have also been implicated in salamander abundance. *Desmognathus tenebrosus* and *Rhyacotriton variegates* displayed higher densities in riffles and pools (Welsh and Ollivier, 1998). Tumlison et al. (1990) observed that *E. tynerensis* were found primarily in slow moving currents. And Wilkins and Peterson (2000) observed that *R. variegates* abundance was negatively associated with the proportion of the stream active channel that had flowing water.

Orser and Shure (1972) found that changes in water velocity and dischage associated with increased urbanization were negatively associated with density of *Desmognathus fuscus*. Similarly Willson and Dorcas (2003) found that average change in cross sectional area between base and peak flow was negatively associated with number of salamanders captured. Barrett et al. (2010) showed that urbanization increased water velocity during storm events and that the increased water flow was detrimental to *Eurycea cirrigera*

larvae, especially where stream substrates consisted of sand and find sediments. Some have concluded that floods negatively affect stream salamanders (Corn et al. 2003), but Rudolph (1978) found no effect of increased water velocity on the spatial patterns of several salamander species, as tested in artificial streams.

For spring-dwelling salamanders, spring discharge is often critical for maintaining appropriate habitat, including thermal and oxygen regimes that support reproduction and viability. Spring discharge decreases during periods of drought (due to decreased aquifer recharge) and when groundwater pumping increases, which often accompanies drought. As spring discharge decreases, water temperature frequently increases and dissolved oxygen decreases (Turner, 2004). Analyzing data on the Barton Springs salamander (*E. sosorum*), Turner (2004) found that the number of salamanders observed at smaller springs (Eliza, Old Mill, and Upper Barton Springs) decreased during periods of low flow.

Temperature

For ectothermic aquatic animals such as salamanders, water temperature affects a number of potentially important parameters, such as metabolic rate, growth, behavior, oxygen concentration of the water, and oxygen consumption. Water temperature is clearly important in determining where stream salamanders are found. Many stream-dwelling salamanders, particularly in the genus *Eurycea*, are confined to relatively cool streams, springs, and caves (Lannoo, 2005). Bowles et al. (2006) observed that Jollyville Plateau salamanders were negatively correlated with the standard deviation of water

temperature—in other words, they were more likely to occur in constant-temperature springs. Pierce et al. (2010) found that Georgetown salamander density was inversely related to distance from the spring origin, although whether this is due to more constant water temperature at the spring origin is not known. Similarly, Sweet (1982) observed that *Eurycea* salamanders on the Edwards Plateau tended to be found in close proximity to spring outflows, which he suggested was due to the narrow thermal tolerance limits of the salamanders.

Orser and Shure (1972) found a negative association between temperature and salamander density in *Desmognathus fuscus*, and Tupa and Davis (1976) concluded that constant thermal conditions were positively associated with salamander densities in *E. nana*. However, using an artificial stream, Rudolph (1978) found that temperature had no relationship to spatial patterns of several species of stream salamanders (*E. lucifuga*, *E. longicauda*, *E. tynerensis*, *E. multiplicata*, and *T. spelaeus*). Other studies (Bowles et al., 2006; Pierce et al., 2010) have found higher surface abundance of salamanders in spring and summer months, but whether this is related to temperature or other environmental factors was not known.

While water temperature appears to be important in habitat selection, some physiological studies suggest that *Eurycea* salamander can tolerate, at least for short periods of time, considerably higher water temperatures than those typically found in habitats where the salamanders occur. For example, Berkhouse and Fries (1995) measured the thermal maximum of adult and juvenile *E. nana* salamanders. The first observable effect of

increasing water temperature occurred at 29-30°C, at which temperature the salamanders became more active. At 35.8^{o}C, adult salamanders lost the ability to right themselves; for juveniles, loss of righting ability occurred at a lower temperature (34.3^{o}C). At even higher temperatures (37.2^{o}C for adults and 35.8^{o}C for juveniles) the salamander exhibited body spasms. These thermal maxima were somewhat higher that those observed for other species of *Eurycea*; for example Hutchinson observed the onset of spasms at 32.1^{o}C in juvenile *E. bislinenata*, at 35.0^{o}C in adult *E. lucifuga*, and at 35.9^{o}C in adult *E. longicauda*. Although these studies might suggest that *Eurycea* salamanders are able to tolerate relatively high water temperatures for short periods of time, negative long-term direct and indirect effects on the salamanders are likely to occur at much lower temperatures.

Water Chemistry

A number of studies provide evidence that water chemistry is a significant limiting factor for some salamanders that occupy streams and springs. For example, Willson and Dorcas (2003) found that dissolved oxygen was positively associated with the number of *Eurycea cirrigera* they captured. Orser and Shure (1972) also found that dissolved oxygen was positively correlated with salamander density in *Desmognathus fuscus*.

Turner (2004) analyzed the relationship between dissolved oxygen and salamander abundance, as measured by surface counts, for the Barton Springs salamander, *E. sosorum* She found a strong and positive but complex relationship between oxygen levels and salamander abundance, with a lag of about 6 months between low oxygen

levels and low numbers of salamanders. Turner suggested that that when dissolved oxygen is low, salamander reproduction decreases and the effect of low reproduction is seen in the number of salamanders observed in the population about six months later. However, dissolved oxygen at Barton Springs is correlated with spring discharge, so it is difficult to know whether the reduced numbers of salamanders are the result of low oxygen or other effects associated with low discharge.

Woods et al. (2010) conducted an extensive study of the effects of low dissolved oxygen on spontaneous activity, metabolic rate, mortality, and juvenile growth rates of *E. nana* and *E. sosorum*, two species closely related to the Georgetown salamander. They found that these salamanders exhibited a clear onset of activity when dissolved oxygen dropped to between 2.7 and 5.5 mg O_2/L, most likely representing an attempt to escape low oxygen levels and move into areas of higher oxygen concentration. Metabolic rates of the salamanders declined at lower oxygen concentrations, particularly below 3 mg O_2/L. Mortality of adults increased below 4 O_2/L, with a 28-day LC_{50} (concentration at which 50% mortality occurs) of 3.4 O_2/L. Growth rates of *E. nana* juveniles decreased considerably at 4.4 O_2/L, but the differences were not statistically significant. The investigators suggested that oxygen levels below 4.4 O_2/L would likely lead to a significant reduction in juvenile growth. In summary, Wood et al. found that low concentrations of dissolved oxygen had multiple deleterious effects on the salamanders, but not until levels dropped below 4.5 O_2/L.

Conductivity is a measure of the electrical conductance of the water and is related to the concentration of ions in the water. Willson and Dorcas (2003) and Bowles et al. (2006) found that conductivity was negatively correlated with number of salamanders captured. Both studies found associations between conductivity and urbanization and concluded that increased conductivity was associated with lower water quality. Corn et al. (2003) concluded that water pollution was negatively associated with salamander health and survival.

Other Habitat Parameters

The abundance of stream-dwelling salamanders has been correlated with several additional habitat parameters. Orser and Shure (1972) observed that salamander abundance was positively associated with stability of the bank soils. Tumlison et al. (1990) found that salamander occurrence was negatively associated with water depth, and Grant et al. (2009) found that salamander occupancy was higher in higher order streams. Other studies have found positive associations between salamanders and reliability of the stream habitat (Sweet, 1982), topographic relief (Sweet, 1982), stream width and elevation (Stoddard and Hayes, 2005), and frequencies of pools (Wilkins and Peterson, 2000).

Disease

The chytrid fungus *Batrachochytridium dendrobatidis* can cause disease in amphibians (particularly frogs) and has been implicated in numerous amphibian declines world-wide (Wake and Vredenburg, 2008; Voyles et al. 2009). Gaertner et al. (2009) detected the

fungus in samples of five central Texas *Eurycea* salamanders (*E. neotenes, E. pterophila, E. nana, E sosorum, and E. tonkawae)* but none of the animals exhibited disease symptoms.

Implications for Conservation and Management of the Georgetown Salamander

This review of the research literature points to several environmental factors that are potentially important in developing conservation and management strategies for the Georgetown salamander (Table 1). A number of studies indicate that urbanization is negatively correlated with presence and abundance of stream and spring-dwelling salamanders (Orser and Shure, 1972; Grant et al., 2001; Willson and Dorcas, 2003; Bowles et al., 2006; Price et al., 2006; Miller et al., 2007; Barrett et al., 2010). This is not surprising—urbanization potentially impacts the salamanders in a number of ways but principally by altering water quality and water flow within the salamander habitat. At least one study (Willson and Dorcas, 2003) demonstrated that the negative effects of urbanization were not confined to the immediate vicinity of salamander habitat, but were watershed-wide in their effects.

Table 1 – Potential Effects of Environmental and Biological Factors on the Abundance of Stream Salamanders. In the table, – indicates negative effect, + indicates positive effect, and o indicates no effect. See text for references documenting these effects.

Environmental Factor	Effect
Urbanization	–
Impervious cover	–
Sedimentation	–
Decreased water quality	–
Increased variation in water velocity	–
Stream gradient	+
Increases in interstitial spaces	+
Road density	–
Timber harvest	–
Presence of rock and cobble	+
Predatory fish	–
Crayfish	–/o
Macroinvertebrates	+/o
Variation in water temperature	–
Oxygen levels	+
Increased nutrients (eutrophication)	–

For the Georgetown salamander, urbanization is also likely to be detrimental and its effects are likely to extend beyond the immediate vicinity of salamander habitat. The quality and quantity of water in the springs where salamanders occur are affected by activities taking place within the recharge zone of individual springs. Unfortunately, the extent and location of recharge zones are often poorly known for individual springs.

Potential negative effects of urbanization on the Georgetown salamander include (1) increases in impervious cover, which limits recharge of the aquifer; (2) increases in pumping of groundwater, which lowers the aquifer and affects spring flow; (3) groundwater pollution; (4) local runoff in the immediate vicinity of the salamander habitat, which introduces sediment, organic matter, and other contaminants directly into the salamander habitat, and (5) introduction of exotic plant and animal species (i.e. taro, aquatic plants, aquarium fish) that may adversely impact salamander populations and their habitat. Activities that maintain the integrity of the aquifer will benefit salamander populations, as will land use and construction practices that prevent the introduction of sediment and pollution into salamander habitats. In choosing salamander populations to target for conservation efforts, it would be helpful to determine the recharge areas of springs and watershed catchments where salamanders are found and to select sites where urbanization is likely to be less intense.

Associated with urbanization is increased density of roads. Several studies have found species-specific effects of roads on salamander populations (Welsh and Ollivier, 1998; Ward et al., 2008). Roads may negatively impact salamanders by increasing impervious

cover and introducing contaminants into the groundwater. Road construction in the immediate vicinity of salamander habitat may be detrimental by introducing fine sediments into the spring flow. In selecting salamander sites to preserve, existing and projected road density might be considered. Conservation and management practices should seek to limit construction of roads within the immediate vicinity of salamander populations, and construction methods that prevent the flow of sediment and storm runoff into springs should be employed.

Timber harvest has been shown to negatively impact stream salamanders (Corn et al., 2003), but little commercial timber harvest occurs within the range of the Georgetown salamander. Nevertheless, research on timber harvesting indicates that removing streamside vegetation can potentially harm salamanders by decreasing canopy cover, with associated increases in solar radiation and stream temperature. Removal of streamside vegetation (even non-native vegetation) from salamander sites should be carried out only after careful consideration of its effect on solar radiation and thermal properties of the spring flow. Removal of streamside trees can also reduce leaf litter, which is often an important carbon source supporting aquatic communities. Another potentially negative effect of removing streamside vegetation is the inadvertent introduction of sediment into the spring flow.

Several studies have shown the importance of rock and cobble substrate and other cover objects for stream salamanders (Orser and Shure, 1972; Tuba and Davis, 1976; Wilson and Dorcas, 2003; Bonett and Chippindale, 2006; Bowles et al., 2006). Research on the

Georgetown salamander (Pierce et al., 2010) confirms the importance of large rocks and cobble in the habitat of these animals. Many studies emphasize the importance of interstitial spaces, provided by rocky habitat, in the ecology of stream-dwelling *Eurycea* salamanders. Conservation practices that maintain and enhance the presence of large rocks within spring flows are likely to benefit the Georgetown salamander.

Increases in sediment represents one of the most significant and yet preventable threats to the Georgetown salamander. Sand, silt and other fine sediment fill interstitial spaces in the streambed substrate and degrade salamander habitat (Orser and Shure, 1972; Tumlison et al., 1990; Welsh and Ollivier, 1998; Bonett and Chippindale, 2006). Sedimentation is more detrimental in low-graduate streams (Corn and Bury, 1989; Ward et al., 2008). Input of sediment into streams and springs occurs through construction, land clearing, and other small-scale disturbances. Because the Georgetown salamander occurs in a limited number of spring flows, usually within limited catchment areas, preventing the input of sediment into these habitats should be achievable.

Fish are known predators on salamanders (Rudolph, 1978; City of Austin, 2001; Lowe and Bolger, 2002; Epp and Gabor, 2008) and are probably important in limiting the distribution of many salamander species to small headwater springs and streams where fish are absent. Management practices should take care not to introduce fish into salamander habitats, nor modify existing salamander habitats in ways that would facilitate natural fish introductions. Although crayfish are potential predators on salamanders, crayfish are found at almost all known sites where Georgetown salamanders

occur. Some studies suggest that crayfish do not negatively impact the salamanders (Bowles et al., 2006; Pierce et al., 2010), although crayfish predation on *Eurycea* salamanders has been observed (Nathan Bendik, personal communication). The effect of crayfish presence on salamander populations warrants further study.

Although the precise diet of the Georgetown salamander is unknown, all salamanders area obligate carnivores and stream salamanders prey on small aquatic invertebrates such as amphipods, planarians, copepods, isopods, mayfly nymphs, and fly larvae. Management practices at salamander sites should seek to maintain habitat characteristics that promote high density of invertebrates.

Water flow and velocity are critical habitat parameters for many spring and stream salamanders, but the optimal requirements vary from species to species (Orser and Shure, 1972; Tumlison et al., 1990; Welsh and Ollivier, 1998; Willson and Dorcas, 2002; Corn et al., 2003; Bowles et al., 2006; Pierce et al., 2010). Management practices for the Georgetown salamander should avoid habitat alterations to the watershed and immediate terrestrial habitats that alter flow regimes. Increases in impervious cover and vegetation changes in the surrounding watershed may lead to greater variance in water velocity, particularly during storm events, which is negatively associated with the abundance of many salamanders (Orser and Shure, 1972; Willson and Dorcas, 2002). Artificial impoundments within spring flows, which reduce water velocity, are also likely to have negative effects on the salamanders. Impoundments may also allow the establishment of fish, which may prey on salamanders.

Eurycea salamanders are most often found in relatively cool aquatic habitats; those species occupying the Edwards Plateau in Texas are probably confined to springs and caves, at least in part, because of their narrow thermal tolerances and the relatively constant water temperatures at these sites (Sweet, 1982). Any habitat modifications that increase water temperature within the spring run, such as removal of vegetative canopy or changes in flow regimes, are likely to have negative effects on the salamanders.

Fast-moving, well oxygenated water appears to be important for the success of many surface-dwelling species of *Eurycea*. Although the oxygen tolerance limits of the Georgetown salamander are unknown, sites where the species occurs are characterized by high levels of dissolved oxygen (typically 6-8 mg/l). Oxygen levels of aquatic systems are often reduced through the input of nutrients into the system. Increased nutrients such as nitrogen and phosphorous (eutrophication) often leads to increases in biological productivity which, in turn, reduces oxygen concentration and increases temperature, sedimentation, and water clarity. Eutrophication also frequently causes changes in invertebrate communities. Common source of nitrogen and phosphorous in urban environments are fertilizer and sewage. These inputs are likely to be detrimental to the Georgetown salamander.

An important but unanswered question is: To what degree does gene flow occur among populations of central Texas *Eurycea*? This is an important issue, because the amount of migration and migration routes can be important in formulating management and

conservation strategies. If substantial migration occurs among populations, then the risk of population extinction is reduced and several populations can be potentially managed as a unit. If, on the other hand, little or no migration occurs among populations, then each population is independent evolutionary unit. Risk of extinction is increased, especially if local population sizes are low. If local extinction occurs, there will be little probability that the site will be recolonized.

Lucas et al. (2009) explored the issue of gene flow among populations of central Texas *Eurycea* using DNA sequence data from salamanders collected from seven spring sites on the Edwards Plateau. These salamanders have been assigned to three named species: *E. nana*, *E. pterophila*, and *E. neotenes*. Based on data from one nuclear gene (*rag1*) and one mitochondrial gene (*ND4*), Lucas et al. detected little gene flow among the seven populations. In fact, they were unable to reject a model of complete genetic isolation among the populations sampled. They found no evidence that aquifers or rivers serve as corridors for dispersal among the populations. They concluded that spring-associated populations of *Eurycea* salamanders occupying the Edwards Plateau are genetically isolated. Whether similar genetic isolation occurs among populations of the Georgetown salamander is presently unknown.

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