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Refined Impervious Cover Analysis for the Four Central Texas Salamanders Currently Proposed for Listing and Designation of Critical Habitat

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Introduction

Impervious cover is any surface material, such as roads, rooftops, sidewalks, patios, paved surfaces, or compacted soil, that prevents water from filtering into the soil (Arnold and Gibbons 1996, p. 244). Once natural vegetation in the area draining into a stream (watershed) is replaced with impervious cover, rainfall is converted to surface runoff instead of filtering through the ground (Schueler 1991, p. 114). Large-scale changes in how water moves within of a watershed can have significant impacts on streams and the organisms that rely on those streams.

Increases in impervious cover cause measurable stream degradation (Klein 1979, p. 959; Bannerman *et al.* 1993, pp. 251–254, 256–258; Center for Watershed Protection 2003, p. 91; Coles et al. 2012, p. 4). This decline in aquatic habitat quality has demonstrable impacts on biological communities within streams. For example, Schueler (1994, p. 104) found that sites receiving runoff from high impervious cover drainage areas had sensitive aquatic macroinvertebrate species replaced by species more tolerant of pollution and hydrologic stress (high rate of changes in discharges over short periods of time). Impervious cover degrades stream habitat in three ways: (1) introducing and concentrating contaminants in surface runoff, (2) increasing the rate at which sediment is deposited into a stream, and (3) altering the natural flow regime of streams.

In our August 22, 2012, proposed rule (77 FR 50768), we calculated impervious cover within the watersheds occupied by the four central Texas salamander species to identify the extent and magnitude of the current impervious cover threat on these species. The four salamander species are the Austin blind salamander (*Eurycea waterlooensis*), Jollyville Plateau salamander (*Eurycea tonkawae*), Georgetown salamander (*Eurycea naufragia*), and Salado salamander (*Eurycea chisholmensis*). This analysis used the nationally consistent Watershed Boundary Dataset to delineate 15 watersheds occupied by the four central Texas salamander species. Although the data for this impervious cover analysis were derived using the finest scale hydrologic units that we were aware of in the Watershed Boundary Dataset (12-digit HUCs), they were too large to offer any reference to the location of salamander-occupied spring sites in relation to the location of impervious cover within the watersheds. In other words, impervious cover occurring within each 12-digit HUC may not necessarily be an indicator of how much impervious cover is impacting water quality within known salamander sites because this analysis did not take into account whether the salamander sites are found upstream or downstream of impervious surfaces associated with developed areas in the HUC.

The goal of the analysis presented here is to calculate impervious cover within the watersheds occupied by the four central Texas salamander species currently proposed for listing at a finer scale. This analysis will identify the surface areas that drain into surface salamander sites and which of these sites may be experiencing habitat quality degradation as a result. We believe the results give a more accurate description of the status of the salamander sites than the analysis performed with the larger 12-digit HUC. We also compare the results of our refined impervious cover analysis with two additional impervious cover analyses conducted by SWCA Environmental Consultants (SWCA) and the City of Austin (COA).

Methods

Watershed delineation

To calculate impervious cover within the watersheds occupied by the four central Texas salamander species, we used a combination of the NHDPlus dataset (http://www.horizon-systems.com/NHDPlus/NHDPlusV1_12.php) and a digital elevation layer developed by the U.S. Geological Survey (USGS) (http://seamless.usgs.gov/ned13.php) to delineate the watersheds of each surface site where these species are known to occur. Because we only delineated the area of land draining into surface habitat, cave locations for each salamander were omitted from the analysis. NHDPlus is a nationally consistent watershed dataset developed by the U.S. Environmental Protection Agency and USGS, based on the National Hydrography Dataset (NHD). NHDPlus integrates the NHD with the National Elevation Dataset (NED) and the Watershed Boundary Dataset (WBD) to produce the smallest (or finest scale) of hydrologic units available: the 14-digit HUC (USGS 2011, pp. 7-8). We used ESRI software to create an aspect map and a set of 5-foot contour lines to help guide creation of even smaller watersheds that specifically drain into salamander spring sites (we termed these "springsheds"). Salamanders have been found up to 164 feet (ft) [50 meters (m)] from a spring opening (Pierce *et al*. 2011a, p. 4), so watersheds were delineated based upon the point 164 ft (50 m) downstream from a salamander site. Spring sites were grouped together if they were located 164 ft (50 m) or less downstream from another site. Ten spring sites total were grouped, including eight for the Jollyville Plateau salamander and two for the Salado salamander.

Impervious cover layer

For the impervious cover layer, we used the 2006 National Land Cover Dataset (MRLC 2012, p. 1). The 2006 National Land Cover Dataset (the most recent of the national land cover datasets) was developed by the Multi-Resolution Land Characteristics Consortium to provide 98 ft^2 (30 m^2) spatial resolution estimates for tree cover and impervious cover percentages within the contiguous United States. An impervious cover value (0 to 100 percent) is assigned for each 98 ft^2 (30 m^2) pixel within the 2006 National Land Cover Dataset. Using these values, we calculated the overall average impervious cover value (percentage) for each springshed identified. We also grouped each pixel into three categories of impervious cover: (1) 0 percent impervious cover (no impervious cover was identified within the 98 ft^2 (30 m^2) pixel), (2) 1 to 10 percent impervious cover (between 1 and 10 percent of the 98 ft^2 (30 m^2) pixel was identified as impervious cover), and (3) greater than 10 percent impervious cover (more than 10 percent of the 98 ft^2 (30 m^2) pixel was identified as impervious cover). To help understand how the impervious cover was distributed throughout the watershed, we calculated the percentage of pixels that fell into each of these three categories for each springshed. We could then determine if the overall impervious cover was being influenced by a few highly impervious pixels or if impervious cover was more evenly distributed throughout the springshed. We believe that this analysis is most likely an underestimation of current impervious cover because small areas of impervious cover may have gone undetected at the resolution of our analysis and additional areas of impervious cover may have been added since 2006.

Impervious cover threshold

The impervious cover categories were chosen based on ecological thresholds reported in the literature. An ecological threshold is the point at which there is an abrupt shift in the quality of an ecosystem, or where small changes in an environmental driver produce large responses in an ecosystem (Groffman *et al.* 2006, p. 1). In our analysis, the ecosystem is a spring-fed stream and the environmental driver is the level of impervious cover within the springshed. The point at which a certain level of impervious cover begins to negatively affect the stream ecosystem is a valuable tool for aquatic species management (Hilderbrand *et al*. 2010, pp. 1010, 1014).

Table 1 presents a summary of studies that report watershed impervious cover thresholds based on a variety of degradation measurements. Most studies examined biological responses to impervious cover (for example, aquatic invertebrate and fish diversity), but several studies measured chemical and physical responses as well (for example, water quality parameters and stream channel modification). Ten percent was the most commonly reported threshold, with more recent studies trending towards thresholds 10 percent and lower. Based on this literature review, we determined that detrimental effects to salamander habitat are likely to begin having significant negative impact on salamander populations at 10 percent impervious cover in a springshed. This is in agreement with our most relevant study, Bowles *et al*. (2006, pp. 113, 117-118), which found lower Jollyville Plateau salamander densities in watersheds with more than 10 percent impervious cover. To our knowledge, this is the only peer-reviewed study that examined watershed impervious cover effects on salamanders in our study area. This is also in agreement with the Center for Watershed Protection's impervious cover model, which predicts that stream health begins to decline at five to 10 percent impervious cover in small watersheds (Schueler *et al*. 2009, pp. 309, 313). Their prediction is based on a meta-analysis of 35 recent research studies (Schueler *et al*. 2009, p. 310).

SWCA Analysis

We received data from an impervious cover analysis conducted by SWCA Environmental Consultants for Williamson County, Texas (SWCA 2012). This impervious cover analysis was conducted on springsheds for 9 Jollyville Plateau salamander sites, 12 Georgetown salamander sites, and 1 Salado salamander site. Although these springsheds are similar to the springsheds that we delineated, there are some differences in the total number of acres analyzed per springshed due to different methods of delineation. For example, while our analysis delineated springsheds based upon the point 164 ft (50 m) downstream from a salamander site, SWCA delineated springsheds based upon the salamander site (spring opening) itself.

For a base set of data, SWCA obtained images from 2010 from the Texas Natural Resource Information System (TNRIS) website (http://www.tnris.org/get-data?quicktabs_maps_data=1). To process the images and perform classification, ESRI's ArcInfo 10 was used. Image classification was performed using to two different methods, namely Iso Cluster Unsupervised Classification and Interactive Supervised Classification. The best method of classification was determined through trial and error for each image set and used the best end result which approximated impervious ground cover. SWCA also incorporated the Strategic Mapping Program's (StratMap) file of Texas road centerlines into the final result to correct for shadows

Table 1: Watershed impervious cover thresholds cited in the literature.

Author(s)	Year	Page number(s)	Measure of degradation	Region	Range of impervious cover thresholds cited (%)																			
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dunne and Leopold	1978	699-700	channel dimensions	New Mexico				■																
Klein	1979	959	fish diversity	Maryland										■		■								
Morisawa and LaFlure	1979	345-348	channel enlargement	New York		■																		
Jones and Clark	1987	1051-1054	aquatic invertebrate diversity	northern Virginia															■					
Steedman	1988	498	fish diversity	Ontario										■	■	■								
Schueler and Galli	1992	170-171	fish diversity (10-12% IC), insect diversity (15% IC)	Maryland										■	■	■			■					
Booth and Reinelt	1993	549-550	channel morphology, fish and amphibian populations, vegetation succession, and water chemistry	western Washington										■										
Shaver et al.	1995	451	aquatic macroinvertes	Delaware								■	■	■	■	■	■	■	■					
Maxted and Shaver	1997	500	aquatic invertebrate community	Delaware										■	■	■	■	■	■					
Booth and Jackson	1997	1084	channel stability, bankfull discharge	western Washington										■										
Wang et al.	1997	9	fish community quality	Wisconsin										■	■	■	■	■	■	■	■	■	■	■
Horner et al.	1997	267	aquatic invertebrate diversity, amphibian richness, aquatic plant species richness, woody debris, dissolved oxygen, zinc	Washington					■	■	■	■												
May	1997	86	riparian buffer, woody debris, streamback erosion, salmoniod community, benthic macroinvertebrates	Washington					■	■	■	■	■	■										
Yoder et al.	1999	20	aquatic invertebrate diversity, sensitive fish species	Ohio								■												
Wang et al.	2001	264	fish community quality and baseflow	southeastern Wisconsin								■	■	■	■	■								
Beach	2001	10-11	fish diversity	coastal streams										■										
Stepenuck et al.	2002	1044	aquatic invertebrate community structure	Wisconsin								■	■	■	■	■								
Morse et al.	2003	120-121	aquatic invertebrate community structure	Maine						■														
Bowles et al.	2006	113, 117-118	Jollyville Plateau salamander density and conductivity	Austin										■										
Olivera and DeFee	2007	178-179	stormwater flow and depth	North of Houston, Texas										■										
Conway	2007	312-313	pH, conductivity	New Jersey		■	■	■	■															
Stranko et al.	2008	1227	brook trout abundance	Maryland				■																
Randhir and Ekness	2009	93	amphibian species richness	Massachusetts												■	■							
Utz et al.	2009	562-563	aquatic invertebrate richness	east and southeast USA		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
King and Baker	2010	1002	aquatic invertebrate community + individual taxa	Maryland	■																			
Hilderbrand et al.	2010	1013	aquatic invertebrate taxa	Maryland					■	■	■	■	■	■										
King et al.	2011	1664	aquatic invertebrate taxa	Maryland	■	■																		

cast by tree cover in the images. More details on the methods of this analysis are presented in SWCA's final report (2012, p. 29-30).

We compared maps of SWCA analysis with maps of our analysis and noted visual differences in springsheds and estimated impervious cover within the springsheds. In one case, we could not match a SWCA site (Tributary 7) with any known Jollyville Plateau salamander sites in our database, so this site was not comparable. We also compared our maps to 2010 aerial photos to determine if differences between our data and SWCA's data could be explained by recent development not captured in our 2006 dataset.

COA Analysis

To compare our impervious analysis to COA, we provided them our delineated springsheds for the Jollyville Plateau salamander, which they used to clip their impervious cover data layer. They then provided us with their calculation of impervious cover for each springshed. Because we recently received new locations for the Jollyville Plateau salamander, there are several spring sites for which we do not have COA data. COA's impervious cover data layer was derived from three sources:

1) Impervious Cover Planimetrics: Building and transportation footprints digitized using aerial imagery. This planimetric data (generated by a consultant) is from 2006 and only available within the City of Austin. It excludes sidewalks and residential driveways.
2) Sidewalk and Driveway Assumptions: COA added a factor to the planimetrics to account for the missing sidewalks and driveways. This is based on GIS analysis of single-family residential areas.
3) Land Use Assumptions: For areas where planimetrics are not available (that is, outside City jurisdiction), COA relied on impervious cover assumptions based on different types of land use (also 2006 data).

Land use impervious cover assumptions are used when direct measurements of impervious cover are not available. Assumptions were based on the COA 2006 land use and planimetric data. Land use assignments (for example, single family and multi-family residential, commercial, office, or civic) were made using tax parcels from county appraisal district information. In contrast, planimetric data collected by a consultant for the COA provide a direct measure of impervious cover and consist of building footprints, roads, parking lots, and other features of the built environment.

Parcels representing each land use and their planimetric data were analyzed using common statistical measures to develop the impervious cover assumptions. Measures included the mean, standard deviation, standard error, and confidence intervals. These statistical measures were used when all parcels representing a specific land use could be analyzed. If all parcels within a land use category could not be analyzed, COA used statistics from a set of randomly selected parcels representing that use and applied those sample statistics to the unanalyzed parcels.

Sidewalks and driveways can add significantly to total impervious cover; however, planimetric data collection methods do not account for them on smaller parcels. Direct sidewalk and driveway measurements were made to a set of randomly selected one-half acre or smaller, single-family parcels (LU Code = 120 or 130). These single-family, sub-classes were chosen because of their large size (in total number and area) compared to other land use classes. As before, the mean, standard deviation, standard error, and confidence intervals were calculated.

Maps of COA's data were not available to visually compare to our data (COA provided us with acres of impervious cover only). Because both our set of data and COA's set of data were based on 2006 data, we could not reliably attribute differences in impervious cover percentages to new development. It should be noted that all three analyses are estimations of impervious cover and do not reflect an exact accounting of every impervious surface within the springsheds.

Results

Our estimated impervious cover percentages for each springshed analyzed are presented in Table 2. A total of 113 springsheds were analyzed, encompassing a total of 494,118 acres (ac) (199,963 hectares (ha)). A map of each individual springshed is located in Appendix A.

Table 2: Estimated impervious cover percentages by springshed from our analysis. Omitted cave locations are shown in orange. Summary statistics for each salamander species are presented in blue. The sums of acres and hectares analyzed do not add up to the species total because some springsheds overlapped with each other. Impervious cover percentages over the 10 percent threshold are presented in yellow.

Springshed	Acres Analyzed	Hectares	Percent Impervious	Area impervious (by percent group)		
				0%	1-10%	>10%
Austin Blind Salamander	76,616	31,005	3.37	83.87	8.32	7.81
Parthenia Springs	76,597	30,998	3.37	83.89	8.30	7.81
Eliza Spring	76,615	31,005	3.37	83.87	8.32	7.81
Sunken Garden (Old Mill) Spring	2	1	2.86	14.29	85.71	0.00
Georgetown Salamander	265,212	107,328	0.40	91.0	7.0	1.9
Avant's (Capitol Aggregates)	8,993	3,639	0.70	90.6	7.6	1.8
Bat Well						
Buford Hollow Springs	417	169	0.16	97.8	1.7	0.6
Cedar Breaks Hiking Trail Spring	207	84	0.16	96.5	3.1	0.4
Cedar Hollow Spring	121	49	0.08	94.3	5.7	0.0
Cobb Springs	535	216	0.01	99.5	0.5	0.0

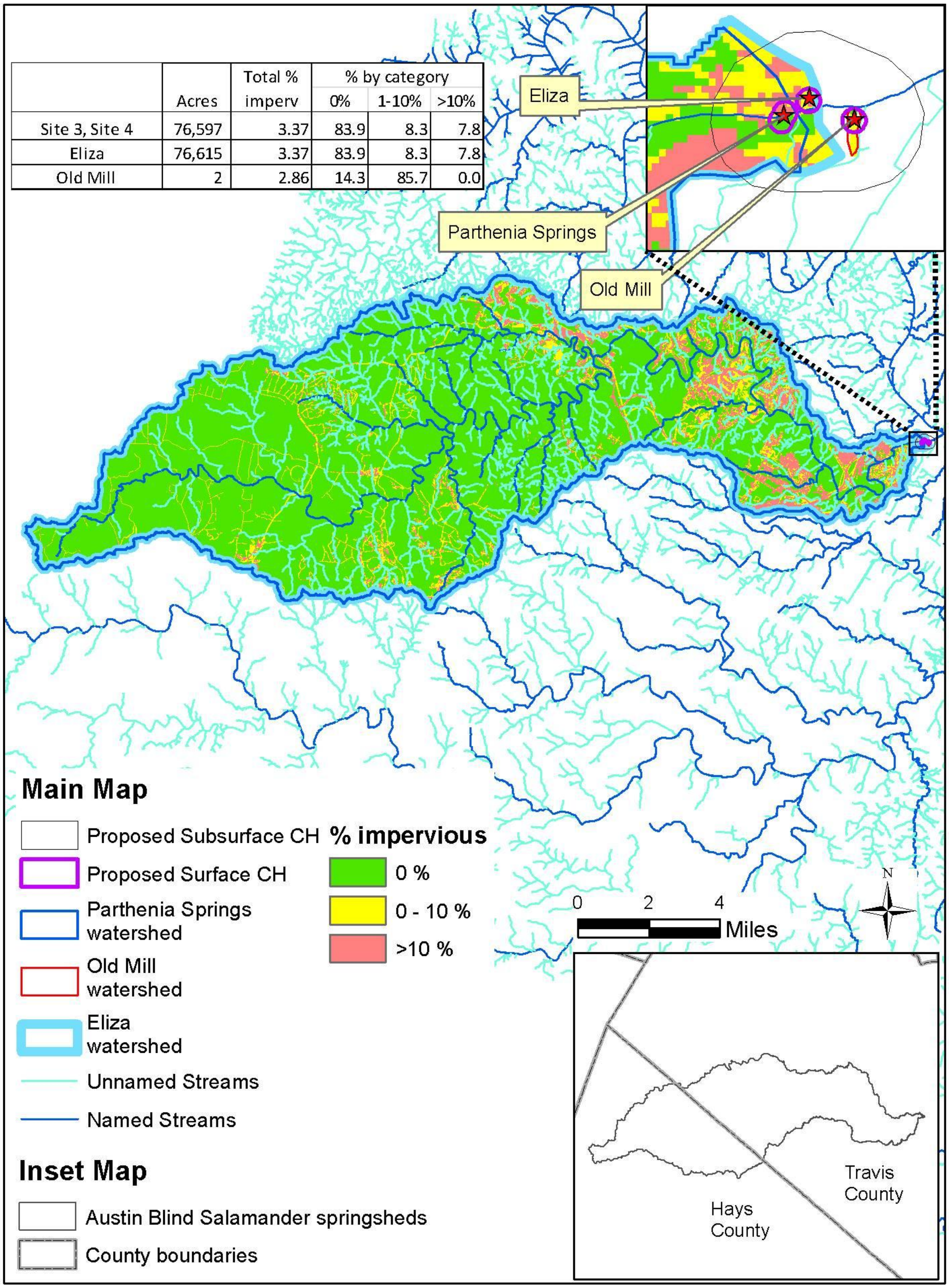
Springshed	Acres Analyzed	Hectares	Percent Impervious	Area impervious (by percent group)		
				0%	1-10%	>10%
Cobb Well						
Cowan Creek Spring	6,660	2,695	0.92	87.6	9.7	2.7
Hog Hollow Spring	83	33	0.00	100.0	0.0	0.0
Knight (Crockett Garden) Spring	7	3	0.00	100.0	0.0	0.0
San Gabriel Spring	258,017	104,416	0.78	91.1	7.0	1.9
Shadow Canyon	25	10	0.74	98.2	0.0	1.8
Swinbank Spring	9	4	6.90	17.9	59.0	23.1
Twin Spring	78	32	3.45	70.1	17.9	12.0
Walnut Spring	1	0	0.00	100.0	0.0	0.0
Water Tank Cave						
Jollyville Plateau Salamander	65,437	26,482	14.81	53.5	14.7	31.7
1	1,736	703	7.14	81.6	5.8	12.7
2	1,659	671	7.48	80.7	6.0	13.3
3, Lanier Spring	1,604	649	7.73	80.1	6.2	13.7
4	1,688	683	7.35	81.1	5.9	13.0
5	648	262	9.45	79.7	4.3	16.0
6	243	98	15.99	64.8	8.9	26.3
9	215	87	20.27	41.0	20.8	38.1
10	235	95	18.50	46.2	19.0	34.8
12	293	119	14.84	56.8	15.3	27.9
13	411	166	10.58	69.2	10.9	19.9
14, Lower Ribelin	520	210	8.37	75.6	8.6	15.8
15	17	7	0.00	100.0	0.0	0.0
16	15	6	0.00	100.0	0.0	0.0
17	788	319	19.16	56.4	5.7	37.9
20	11	5	0.28	98.0	0.0	2.0
21	188	76	26.93	42.1	11.3	46.5
22	31	13	40.60	30.2	12.2	57.6
24	74	30	4.95	76.6	13.2	10.2
25	467	189	0.00	100.0	0.0	0.0
Audubon Spring	23	9	0.00	100.0	0.0	0.0
Avery Deer Spring	246	100	17.66	50.9	10.9	38.2
Avery Springhouse Spring	24	10	45.60	3.6	10.0	86.4
Baker Spring	79	32	0.41	87.4	11.8	0.8
Balcones District Park Spring	2,256	913	33.50	14.8	17.7	67.4

Springshed	Acres Analyzed	Hectares	Percent Impervious	Area impervious (by percent group)		
				0%	1-10%	>10%
Barrow Hollow Spring	183	74	12.19	41.2	22.0	36.8
Barrow Preserve Tributary	124	50	10.76	34.8	28.1	37.1
Blizzard 2 / Blizzard 3	6	3	0.00	100.0	0.0	0.0
Blizzard R-Bar-B Spring	1,557	630	10.24	67.2	9.8	22.9
Bluewater Cave No. 1						
Bluewater Cave No. 2						
Broken Bridge Spring	270	109	22.87	24.9	21.8	53.3
Brushy Creek Spring	49,784	20,147	14.00	55.0	15.2	29.8
Bull Creek at Lanier Tract	660	267	6.59	80.8	6.8	12.4
Bull Creek Spring Pool	1,743	705	7.12	81.6	5.7	12.6
Bull Creek Tributary 5 (2), Bull Creek Tributary 5 (3)	773	313	19.23	56.4	5.6	38.1
Buttercup Creek Cave						
Canyon Creek, Bull Creek Tributary 6 (3)	1,186	480	20.11	34.0	17.6	48.4
Canyon Creek Hog Wallow Spring	726	294	8.43	81.9	3.9	14.3
Canyon Creek Pope and Hiers	851	344	19.67	35.7	16.4	48.0
Cistern (Pipe) Spring	3	1	0.00	100.0	0.0	0.0
Concordia Spring X	17	7	13.53	72.7	0.0	27.3
Concordia Spring Y	322	130	12.89	71.5	6.9	21.6
Fern Gully	151	61	26.93	36.6	11.1	52.3
Flea Cave						
Franklin, Franklin Tract 3	1,829	740	6.78	82.5	5.4	12.0
Franklin Tract 2	1,832	742	6.77	82.5	5.4	12.0
Gardens of Bull Creek	2,099	849	18.76	45.2	12.6	42.2
Gaas Spring	24	10	0.15	85.5	14.5	0.0
Godzilla Cave						
Hamilton Reserve West	554	224	14.55	65.1	10.0	24.9
Hearth Spring	719	291	22.58	21.2	17.8	61.0
Hideaway Cave						
Hill Marsh Spring	146	59	10.21	66.9	14.0	19.1
Horsethief, 18	7	3	0.00	100.0	0.0	0.0
House Spring	93	38	25.96	7.9	36.0	56.1
Hunter's Lane Cave						
Ilex Cave						
Indian Spring	111	45	11.13	24.7	38.8	36.4

Springshed	Acres Analyzed	Hectares	Percent Impervious	Area impervious (by percent group)		
				0%	1-10%	>10%
Ivanhoe Spring 2	11	5	0.00	100.0	0.0	0.0
Kelly Hollow Springs	254	103	23.23	40.3	14.5	45.2
Kretschmarr Salamander Cave						
Krienke Spring	3,235	1,309	8.74	61.2	19.0	19.9
Lanier 90-foot Riffle	814	329	9.89	76.3	6.8	17.0
Little Stillhouse Hollow Spring	26	11	20.46	50.4	9.4	40.2
Long Hog Hollow Tributary Below Fireoak Spring	191	77	24.78	21.5	16.5	62.0
MacDonald Well	535	217	7.82	82.1	3.2	14.7
Moss Gully	26	11	0.00	100.0	0.0	0.0
PC Spring	1,630	660	11.68	69.1	9.2	21.8
Pit Spring	1,823	738	6.80	82.5	5.5	12.1
Ribelin	12	5	0.00	100.0	0.0	0.0
Ribelin 2	416	168	10.46	69.6	10.7	19.7
Ribelin / Lanier	578	234	7.53	78.1	7.7	14.2
Salamander Cave						
Salamander Squeeze Cave						
SAS Canyon	68	28	11.64	59.4	13.6	26.9
Schlumberger Spring # 1, 19	58	24	27.03	49.8	8.0	42.2
Schlumberger Spring #2	86	35	19.82	61.6	6.2	32.2
Sierra Spring	347	140	19.96	16.9	21.8	61.3
Small Sylvia Spring	1,241	502	22.09	17.3	28.2	54.5
Spicewood Spring (USGS), Spicewood Tributary	377	152	30.75	9.8	21.5	68.7
Spicewood Park Dam	259	105	17.96	29.9	20.2	49.9
Spicewood Valley Park Spring, Sylvia Spring Area 4	855	346	21.03	17.0	31.8	51.2
Stillhouse Hollow	44	18	25.20	43.5	8.0	48.5
Stillhouse Hollow Spring	9	4	11.26	57.1	9.5	33.3
Stillhouse Hollow Tributary	67	27	19.83	48.5	10.6	40.9
Stillhouse Tributary	63	25	20.96	45.6	11.3	43.1
Sylvia Spring Area 2, Sylvia Spring Area 3	839	340	20.83	16.9	32.3	50.8
Tanglewood 2	64	26	32.05	6.2	20.0	73.8
Tanglewood Spring, Tanglewood 3	141	57	30.03	11.1	18.4	70.6
Testudo Tube						

Springshed	Acres Analyzed	Hectares	Percent Impervious	Area impervious (by percent group)		
				0%	1-10%	>10%
Three Hole Spring	645	261	9.49	79.6	4.3	16.1
Treehouse Cave						
Tributary Downstream of Grandview	101	41	7.89	72.1	9.6	18.2
Tributary No. 3	640	259	21.34	34.6	15.9	49.5
Tributary 4 shaft - upstream	1,445	585	21.75	20.1	26.2	53.7
Tributary 4 shaft - downstream	1,595	646	21.11	22.0	25.2	52.8
Tributary No. 5	794	321	19.00	56.7	5.7	37.6
Tributary No. 6, Bull Creek Tributary 6 (2)	1,190	482	20.04	34.2	17.5	48.3
Tributary 6 @ Sewage Line	1,178	477	20.22	33.7	17.6	48.7
Troll Spring	129	52	48.29	17.4	7.4	75.3
Tubb Spring	9	4	28.55	26.2	7.1	66.7
TWASA Cave						
Two Hole Cave						
Upper Ribelin	284	115	15.34	55.4	15.8	28.9
Wheless 2	283	115	0.00	100.0	0.0	0.0
Wheless Springs	411	166	0.00	100.0	0.0	0.0
Whitewater Cave						
Salado Salamander	86,853	35,148	0.42	94.0	4.9	1.0
Big Boiling Spring, Lil' Bubbly Spring	86,681	35,079	0.41	94.2	4.9	1.0
Cistern Spring	4,480	1,813	0.04	97.1	2.8	0.0
Lazy Days Fish Farm	172	69	6.42	32.0	47.2	20.9
Hog Hollow Spring	89	36	0.00	100.0	0.0	0.0
Robertson Spring	86,500	35,005	0.38	94.3	4.8	0.9
Solana Spring #1	67	27	0.01	98.7	1.3	0.0

The Austin blind salamander had three springsheds delineated, one for each of the springs where the species is found. Eliza and Parthenia Springs had nearly identical large surface drainage areas, while the springshed of Sunken Garden (Old Mill) was found to be a much smaller area draining to the south (Figure 1). While the average level of impervious cover was low in Eliza and Parthenia springsheds, most of the impervious cover occurs within five miles of the springs (Figure 1).



	Acres	Total % imperv	% by category 0%	1-10%	>10%
Site 3, Site 4	76,597	3.37	83.9	8.3	7.8
Eliza	76,615	3.37	83.9	8.3	7.8
Old Mill	2	2.86	14.3	85.7	0.0

Figure 1: Austin blind salamander springsheds with impervious cover.

For the Jollyville Plateau salamander, a total of 91 springsheds were delineated, representing 102 spring sites. The springsheds varied greatly in size, ranging from the 3 ac (1 ha) springshed of Cistern (Pipe) Spring to 49,784 ac (20,147 ha) springshed of Brushy Creek Spring. Impervious cover also varied greatly among springsheds. Fourteen springs had springsheds with no impervious cover (Wheless, Wheless 2, Ribelin, Moss Gully, Ivanhoe Spring 2, Horsethief, 18, Cistern, Blizzard 2, Blizzard 3, Audubon, 25, 16, and 15). However, 57 of the 91 springsheds had impervious cover levels greater than the 10 percent threshold. The highest level of impervious cover (48 percent) was found in the springshed of Troll Spring. At 14.81 percent, the overall average amount of impervious cover for all Jollyville Plateau salamander springsheds combined exceeded the habitat degradation threshold.

Of the springsheds with average impervious cover levels less than 10 percent, Krienke Spring had the highest percentage of land with 1 to10 percent and >10 percent impervious cover (19 and 19.9 percent, respectively). In other words, 19 percent of the Krienke Spring springshed had a relatively low density of impervious cover, and 19.9 percent of the springshed has passed the 10 percent threshold with relatively high densities of impervious cover. Many other springsheds had comparable percentages of land that had exceeded the 10 percent threshold and where the total springshed impervious cover was less than 10 percent (see Tributary Downstream of Grandview, Ribelin/Lanier Spring, Pit Spring, MacDonald Well, Lanier 90-foot riffle, Franklin Spring, Canyon Creek Hag Wallow Spring, Bull Creek Spring Pool, Bull Creek at Lanier Tract, 24, 14/Lower Ribelin, 5, 4, 3/Lanier Spring, 2, and 1).

For the Georgetown salamander, a total of 13 springsheds were delineated, representing 13 spring sites. The springsheds varied greatly in size, ranging from the 1 ac (0.4 ha) springshed of Walnut Spring to the 258,017 ac (104,416 ha) springshed of San Gabriel Spring. The average impervious cover within each springshed had much lower variation, and most values were well below the 10 percent threshold of sharp stream quality declines. Three springsheds had no impervious cover (Knight Spring, Hogg Hollow Spring, and Walnut Spring) and Swinbank Spring had the highest average amount of impervious cover at 6.9 percent. The springshed of Swinbank Spring also had the highest percentage of land with 1 to 10 percent and >10 percent impervious cover (59 and 23.1 percent, respectively). In other words, 59 percent of the Swinbank Spring springshed had a relatively low density of impervious cover, and 23.1 percent of the springshed has passed the 10 percent threshold with relatively high densities of impervious cover. The largest springshed, San Gabriel Spring, has a low proportion of impervious cover overall. However, Figure 2 reveals that most of the impervious cover is in the area immediately surrounding the spring site. The overall average amount of impervious cover for all Georgetown salamander springsheds combined was 0.4 percent.

	Acres	Total % imperv	Area (percent)		
			0% imperv	1-10% imperv	>10% imperv
San Gabriel Spring	258,017	0.78	91.1	7.0	1.9

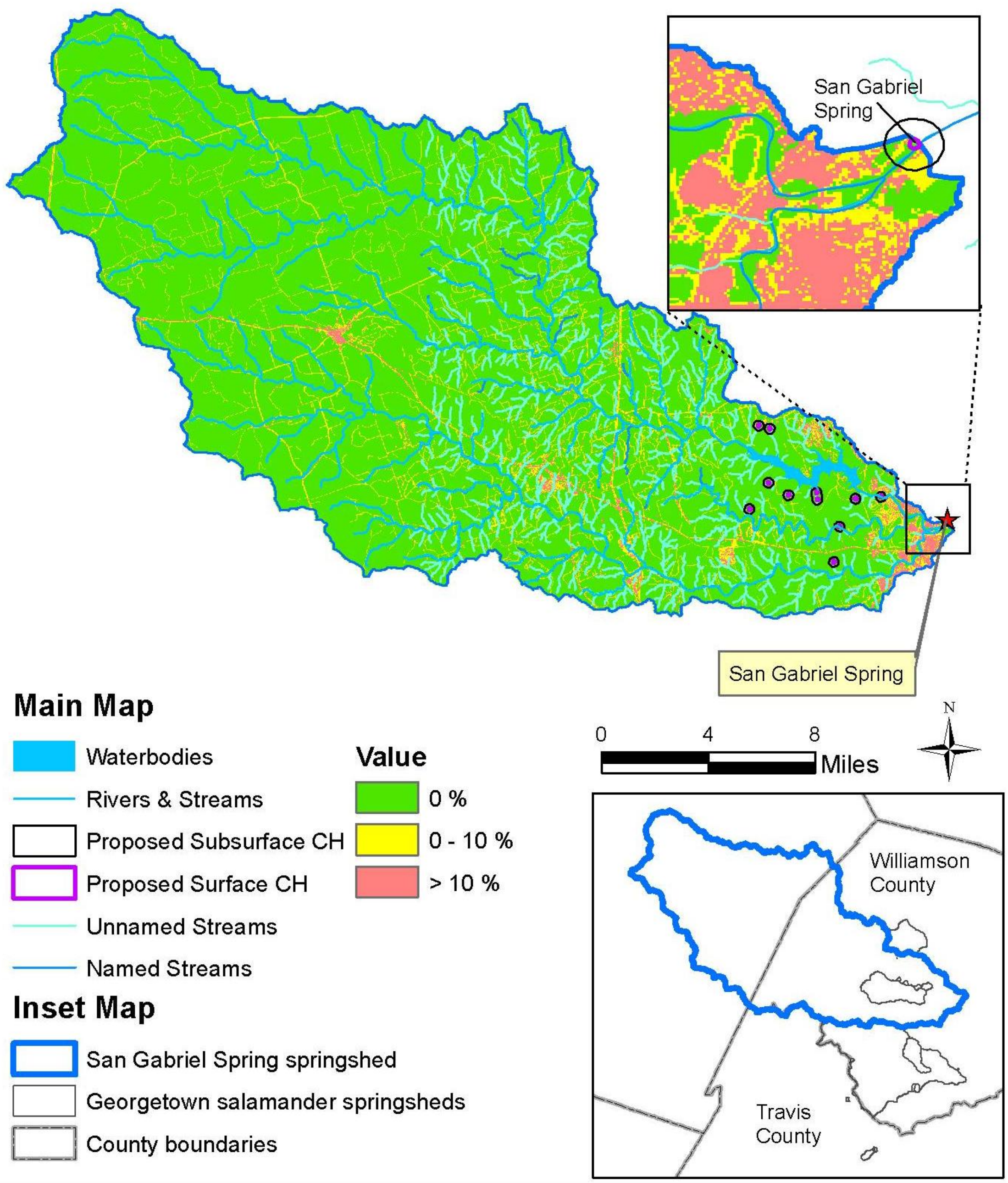


Figure 2: San Gabriel Spring springshed with impervious cover

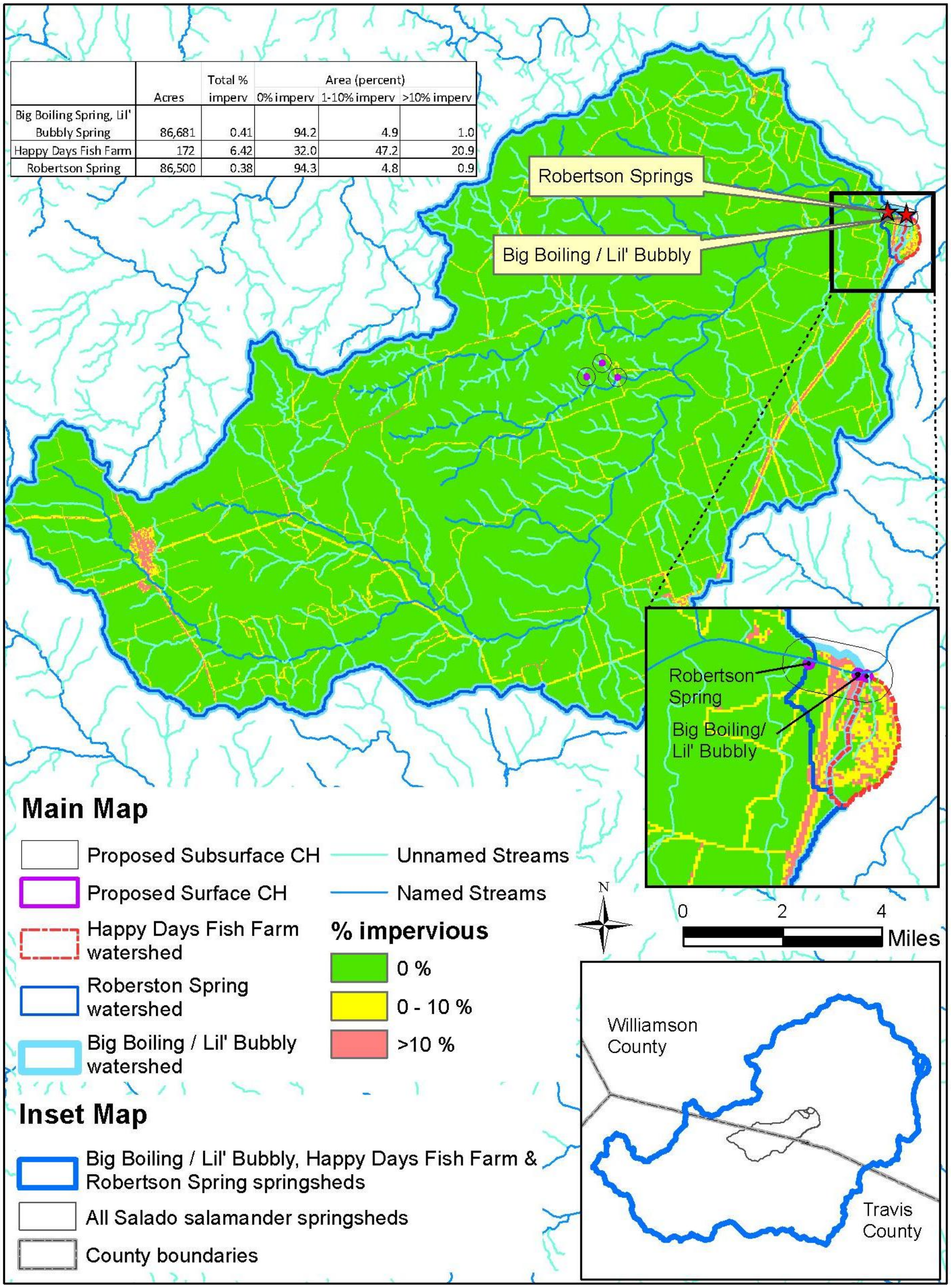
The Salado salamander had a total of six springsheds delineated, representing seven different spring sites. The springsheds ranged in size from the 67 ac (27 ha) springshed of Solana Spring #1 to 86,681 ac (35,079 ha) springshed of Big Boiling and Lil' Bubbly Springs. Five of the six springsheds had impervious cover levels less than one percent, while the springshed of Happy Days Fish Farm had 6.42 percent of impervious cover. About 47 percent of the Happy Day Fish Farm springshed was approaching the 10 percent impervious cover threshold, and approximately 21 percent of the springshed had passed that threshold. Although the largest springshed (Big Boiling and Lil' Bubbly Springs) has a low amount of impervious cover (0.41 percent), almost all of that impervious cover is located within the Village of Salado nearby the spring site (Figure 3). The overall average amount of impervious cover for all Salado salamander springsheds combined was 0.42 percent.

Comparison to SWCA Analysis

A comparison of SWCA, COA, and our data is presented in Appendix B. This table contains the amount of area analyzed (in acres and hectares), the amount of that analyzed area that was categorized as impervious (in acres and hectares), and the percentage of impervious cover for all of the springsheds. The majority of SWCA springsheds were similar in size and shape to the springsheds that we delineated. The remaining SWCA springsheds differed from ours mostly due to our decision to start the delineation 164 ft (50 m) downstream of the site, whereas SWCA started delineation at the site itself. Nonetheless, these springsheds were generally close enough to our own to facilitate comparison in impervious cover data. However, there were two springsheds that were not comparable in terms of impervious cover because SWCA's springsheds were very different from our own (Walnut Spring and Baker Spring).

Impervious cover percentage of each springshed often differed a great deal between our data and SWCA data. Except for one springshed (Audubon Spring), SWCA's percentages were always higher than our own. On seven occasions, SWCA's percentages were higher than the ten percent threshold and our percentage was not. Four out of 12 Georgetown salamander springsheds, and an additional three Jollyville Plateau salamander springsheds (for a total of 60 out of 91 springsheds) have passed this threshold, according to the analysis by SWCA. By examining 2010 aerial photos in ArcGIS, we were able to attribute some of this increase in impervious cover to recent development that our 2006-based analysis did not consider. For example, in the Buford Hollow springshed, we saw a road and part of a quarry in the 2010 aerial photo and the SWCA data layer that was not present in our impervious cover data layer. We measured the area of the road and the quarry and concluded that these features explained about 28 ac (11 ha) of the 37.9 ac (16 ha) difference in impervious area between our data and SWCA's data. Other springsheds that had unaccounted for development include Avant Spring, Cedar Breaks Hiking Trail Spring, Cedar Hollow Spring, Cowen Creek Spring, 3/Lanier Spring, 14/Lower Ribelin, PC Spring, Tributary No. 5, and Upper Ribelin.

Recent development did not explain all of the difference in impervious area between the two datasets. Besides slight differences in watersheds, we attributed the remainder of the impervious area difference to differences in our analysis methods. For example, the impervious cover data that we used attempted to estimate impervious cover in 98 ft (30 m) pixels of land, whereas SWCA's analysis was able to more finely categorize features as impervious using



	Acres	Total % imperv	Area (percent) 0% imperv	1-10% imperv	>10% imperv
Big Boiling Spring, Lil' Bubbly Spring	86,681	0.41	94.2	4.9	1.0
Happy Days Fish Farm	172	6.42	32.0	47.2	20.9
Robertson Spring	86,500	0.38	94.3	4.8	0.9

Figure 3: Big Boiling and Lil' Bubbly Springs springshed with impervious cover

vector data. We noticed that our analysis tended to underestimate the amount of impervious cover compared to SWCA due to this difference in methodology, especially in small springsheds. Upon examination of aerial photos and SWCA impervious cover maps, we also noticed that the SWCA analysis tended to categorize land features such as bare ground, dirt roads, and dry stream beds as impervious where our analysis did not. This was particularly apparent in the watershed of Big Boiling and Lil' Bubbly Springs. As these features are typically not considered 100% impervious, we concluded that SWCA's figures tend to overestimate the amount of impervious cover in a springshed.

Comparison to COA Analysis

Because we provided COA with our springsheds, almost all of COA's springsheds have the same size and shape as our own. However, after COA provided us with their impervious cover analysis of our delineated springsheds, we incorporated new Jollyville Plateau salamander sites and subsequently modified one springshed (Tanglewood Spring/Tanglewood 3). We also added nine springsheds that COA did not analyze.

COA's impervious cover percentage of each springshed was generally closer to our percentages than SWCA's. COA's percentages were generally higher than our own, but there were 11 cases where our percentages were higher. Because we did not have maps of COA's impervious cover, we could not attribute increases in impervious cover to additional development.

Overall, COA analyzed 82 springsheds and 55 of those had impervious cover greater than 10 percent. Five of these 55 springsheds had less than ten percent impervious cover in our analysis (5, 20, Krienke Spring, Lanier 90-foot Riffle, and Tributary Downstream of Grandview).

Discussion

Based on our analysis of impervious cover levels in land draining across the surface into salamander habitat (Table 2), the Jollyville Plateau salamander had the highest number of springsheds with impervious cover levels above the threshold expected to lead to habitat degradation (57 out of 91). Conversely, the springsheds encompassing Austin blind, Georgetown, and Salado salamander habitat were relatively low in impervious cover. The analyses completed by SWCA and COA broadly followed this species-level pattern, although impervious cover percentages at individual sites were generally higher than our own (Appendix B). Compiling all three analyses together, the Jollyville Plateau salamander is estimated to have between 57 and 64 springsheds (out of 91) with more than 10 percent impervious cover, the Georgetown salamander has between 0 and 4 springsheds (out of 13) with more than 10 percent impervious cover, and the Austin blind and Salado salamanders have 0 springsheds with more than 10 percent impervious cover.

Although Table 2 and Appendix B are helpful in determining springshed impervious cover levels in relation to the ten percent threshold, it does not tell the complete story. Large springsheds require examination of where the impervious cover occurs to understand how the salamander site might be affected. For example, San Gabriel Spring's springshed has an average impervious cover of only 1.2 percent (Table 2), but the salamander site is in the middle of a highly urbanized area: the City of Georgetown (Figure 2). The habitat is in poor condition and Georgetown salamanders have not been observed here since 1991 (Chippindale *et al.* 2000, p. 40; Pierce 2011b, pers. comm.). Other studies have demonstrated that the spatial arrangement of impervious cover has impacts on aquatic ecosystems. An analysis of 42 watersheds in Washington found that the spatial configuration of impervious cover is important in predicting aquatic macroinvertebrate communities (Alberti *et al.* 2007, pp. 355-359). King *et al*. (2005, p. 146-147) found that the closer developed land was to a stream in the Chesapeake Bay watershed, the larger the effect it had on stream macroinvertebrates. On a national scale, watersheds with development clustered in one large area (versus being interspersed throughout the watershed) and development located closer to streams had higher frequency of high-flow events (Steuer *et al*. 2010, p. 47-48, 52). Based on these studies, it is likely that the way development is situated in the landscape of a springshed of a salamander spring site plays a large role in how that development impacts salamander habitat. Taking into account the spatial configuration of impervious cover within a springshed is a crucial step in future analyses of these salamander sites.

It must be noted that low levels of impervious cover (that is, less than 10 percent) may also degrade salamander habitat. Recent studies in the eastern U.S. have reported large declines in aquatic macroinvertebrates (the prey base of salamanders) at impervious cover levels as low as 0.5% (King *et al.* 2011, p. 1664; King and Baker 2010, p. 1002). Several authors have argued that impervious cover has a mostly linear effect on aquatic habitat; that is, negative effects to stream ecosystems are seen at low levels of impervious cover and gradually increase as impervious cover increases (Booth *et al*. 2002, p. 838; Groffman *et al*. 2006, pp. 5-6). However, the best available scientific evidence at this time suggests that springsheds with more than 10 percent impervious cover have the most significant impact on salamander populations in this region. For example, COA cited five declining salamander populations in 2006: Balcones District Park Spring, Tributary 3, Tributary 5, Tributary 6, and Spicewood Tributary (O'Donnell *et al*. 2006, p. 4). All of these populations are within springsheds containing more than 10 percent impervious cover (Table 2). Springs with relatively low amounts of impervious cover in their springshed tend to have generally stable or increasing salamander populations (see Franklin and Wheless Springs; Bendik 2011, pp. 18-19).

Because we used the 2006 National Land Cover Dataset to calculate impervious cover, impervious cover values within the springsheds of the four salamander species may be higher at the time of this report. Between 2006 and 2009, the human population in Travis County increased from 928,037 (Texas State Data Center 2006, p. 6), to 1,012,789 (Texas State Data Center 2009, p. 7), representing an increase of 9.1 percent. Williamson County population increased from 349,982 in 2006 (Texas State Data Center 2006, p. 7) to 408,128 in 2009, a 16.6 percent increase (Texas State Data Center 2009, p. 8). Bell County population increased from 269,073 in 2006 (Texas State Data Center 2006, p. 1) to 284,408 in 2009, a 5.7 percent increase (Texas State Data Center 2009, p. 1). Development in the area may have also increased to accommodate the growth in these areas. We saw evidence of impervious cover growth within the springsheds by comparing our data to SWCA's data, which was based on 2010 aerial photography. SWCA also examined impervious cover changes from 1996 to 2010 and found increases in 11 of the 12 Georgetown salamander sites (SWCA 2012, p. 31). Future analyses should attempt to use more current impervious cover estimates and compare them to the values presented in this analysis to understand how threats to the salamander species are changing over time.

One major limitation of this analysis is that we only examined surface drainage areas (springsheds) for each spring site. In addition to the surface habitat, the four central Texas salamanders use the subsurface habitat. Moreover, the base flow of water discharging from the springs on the surface comes from groundwater sources, which are in turn replenished by recharge features on the surface.   As Shade *et al*. (2008, p. 3-4) point out ". . . little is known of how water recharges and flows through the subsurface in the Northern Segment of the Edwards Aquifer. Groundwater flow in karst is often not controlled by surface topography and crosses beneath surface water drainage boundaries, so the sources and movements of groundwater to springs and caves inhabited by the JPS are poorly understood. Such information is critical to evaluating the degree to which JPS sites can be protected from urbanization." So, a recharge area for a spring may occur within the surface springshed, or it could occur many miles away in a completely different watershed. A site completely surrounded by development may still contain unexpectedly high water quality because that spring's base flow is coming from a distant recharge area that is free from impervious cover stressors. While some dye tracer work has been done in the Northern Segment (Shade *et al.* 2008, p. 4), clearly-delineated recharge areas that flow to specific springs have not been identified for any of these spring sites; therefore, we could not examine impervious cover levels on recharge areas to better understand how development in those areas may impact salamander habitat.

Another limitation of this analysis is that we did not account for riparian (stream edge) buffers or stormwater runoff control measures, both of which have the potential to mitigate some of the effects of impervious cover on streams. Research studies consistently demonstrate that streams with higher levels of riparian vegetation have higher habitat and biological scores (Schueler *et al*. 2009, pp. 312-313). Vegetated riparian areas are effective at buffering streams against the detrimental effects of impervious cover at lower levels, but this buffering quality tends to decrease in effectiveness when impervious cover levels rise above 10 to 15 percent (Schueler *et al*. 2009, p. 313).

In contrast, the effectiveness of stormwater runoff control measures, such as passive filtering systems, is largely unknown in terms of mitigating the effects of watershed-scale urbanization (O'Driscoll *et al*. 2010, p. 614, 616-617; Schueler *et al*. 2009, p. 313). In a survey and information gathering workshop of more than 100 stream ecologists (Wenger *et al*. 2009, p. 1083-1085), key unanswered research questions were formulated, including the following two questions:

> 1) Can retrofitted, dispersed stormwater treatment measures in existing urban areas mimic some of the important ecological and hydrological processes previously performed by headwater streams?

2) Which management actions are likely to achieve improved ecological condition under different levels of impervious cover and different current stream conditions?

Schueler *et al*. (2009, p. 313) notes that the Center for Watershed Protection's impervious cover model has been tested in areas where some degree of stormwater regulation has existed for several decades.

Literature Cited

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., and D. Spirandelli. 2007. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landscape and Urban Planning 80: 345-361.

Arnold, C.L., and C.J. Gibbons. 1996. Impervious surface coverage: the emergence of a key environmental indicator. Journal of the American Planning Association 62: 243-258.

Bannerman, R.T., Owens, D.W., Dodds, R.B., and N.J. Hornewer. 1993. Sources of pollution in Wisconsin stormwater. Water Science & Technology 28:241-259.

Beach, D. 2001. Coastal Sprawl: The effects of urban design on aquatic ecosystems in the United States. Report prepared for the Pew Oceans Commission. 40 pp.

Bendik, N. 2011. Jollyville Plateau Salamander Status Report. City of Austin Watershed Protection. SR-11-10. 43 pp.

Booth, D.B., Hartley, D., and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. Journal of the American Water Resources Association 38 (3): 835-845.

Booth, D.B. and C.R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. Journal of the American Water Resources Association 33 (5): 1077-1090.

Booth, D.B. and L.E. Reinelt. 1993. Consequences of urbanization on aquatic systems—measured effects, degradation thresholds, and corrective strategies. Proceedings of Watershed '93 Conference: 545-550.

Bowles, B.D., Sanders, M.S., and R.S. Hansen. 2006. Ecology of the Jollyville Plateau salamander (*Eurycea tonkawae*: Plethodontidae) with an assessment of the potential effects of urbanization. Hydrobiologia 553: 111-120.

Center for Watershed Protection. 2003. Impacts of impervious cover on aquatic systems. Watershed Protection Research Monograph No. 1. March 2003. 158 pp.

Chippindale, P.T., A.H. Price, Wiens, J.J., and D. M. Hillis. 2000. Phylogenetic relationships and systematic revision of central Texas hemidactyliine plethodontid salamanders. Herpetological Monographs 14: 1-80.

Coles, J.F., McMahon G., Bell A.H., Brown L.R., Fitzpatrick F.A., Eikenberry B.C., Woodside M.D., Cuffney T.F., and Bryant W.L., Cappiella K., Fraley-McNeal L, and W.P. Stack. 2012. Effects of urban development on stream ecosystems in nine metropolitan study areas across the United States. Circular 1373. U.S. Geological Survey. 152 pp.

Conway, T.M. 2007. Impervious surface as an indicator of pH and specific conductance in the urbanizing coastal zone of New Jersey, USA. Journal of Environmental Management 85: 308-316.

Dunne, T. and L.B. Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company: San Francisco. 818 pp.

Groffman, P.M., Baron, J.S., Blett, T., Gold, A.J., Goodman, I., Gunderson, L.H., Levinson, B.M., Palmer, M.A., Paerl, H.W., Peterson, G.D., Poff, L., Rejeski, D.W., Reynolds, J.F., Turner, M.G., Weathers, K.C., and J. Wiens. 2006. Ecological Thresholds: The key to successful environmental management or an important concept with no practical application? Ecosystems 9: 1-13.

Hilderbrand, R.H., Utz, R.M., Stranko S.A., and R.L. Raesly. 2010. Applying thresholds to forecast potential biodiversity loss from human development. Journal of the North American Benthological Society 29 (3): 1009-1016.

Horner, R.R., Booth, D.B., Azous, A., and C.W. May. 1997. Watershed determinants of ecosystem functioning. Effects of watershed development and management on aquatic ecosystems: proceedings of an Engineering Foundation Conference on August 4-9, 1996. 494-512.

Jones, R.C. and C.C. Clark. 1987. Impact of watershed urbanization on stream insect communities. Water Resources Bulletin 23 (6): 1047-1055.

King, R.S., Baker, M.E., Whigham, D.F., Weller, D.E., Jordan, T.E., Kazyak, P.F., and M.K. Hurd. 2005. Spatial considerations for linking watershed land cover to ecological indicators in streams. Ecological Applications 15 (1): 137-153.

King, R.S. and M.E. Baker. 2010. Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. Journal of North American Benthological Society 29 (3): 998-1008.

King, R.S., Baker, M.E., Kazyak, P.F., and D.E. Weller. 2011. How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization. Ecological Applications 21(5): 1659-1678.

Klein, R.D. 1979. Urbanization and stream impairment. Water Resources Bulletin. American Water Resources Association 15: 948-963.

Maxted, J. and E. Shaver. 1997. The use of retention basins to mitigate stormwater impacts on aquatic life. Effects of watershed development and management on aquatic ecosystems: proceedings of an Engineering Foundation Conference on August 4-9, 1996. 494-512.

May, C.W., Horner, R.R., Karr, J.R., Mar, B.W., and E.B. Welch. 1997. Effects of urbanization on small streams in the Puget Sound ecoregion. Watershed Protection Techniques 2 (4): 483-494.

Morisawa, M. and E. LaFlure. 1979. Hydraulic geometry, stream equilibrium, and urbanization. Adjustments of the fluvial system: a proceedings volume of the tenth annual geomorphology symposia series held at Binghamton, New York, September 21: 333-350.

Morse, C.C., Huryn, A.D., and C. Cronan. 2003. Impervious surface area as a predictor of the effects of urbanization on stream insect communities in Maine, U.S.A. Environmental Monitoring and Assessment 89: 95-127.

MRLC (Multi-Resolution Land Characteristics Consortium). 2012. National landcover database. [Accessed January 23, 2012]. http://www.mrlc.gov

O'Donnell, L., Turner, M., Sanders, M., Geismar, E., Heilman, S., and L. Zebehazy. 2006. Summary of Jollyville Plateau salamander data (1997-2006). City of Austin Watershed and Development Review Department. December 2006. 50 pp.

O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., and S. McMillan. 2010. Urbanization effects on watershed hydrology and in-stream processes in the southern United States. Water 2: 605-648.

Olivera, F. and B.B. DeFee. 2007. Urbanization and its effect on runoff in the Whiteoak Bayou watershed, Texas. Journal of the American Water Resources Association 43 (1): 170-182.

Pierce, B. 2011a. Report on ecological studies of the Georgetown salamander (*Eurycea naufragia*) at two sites in Williamson County, Texas, May 2010 - April 2011. Report to the Williamson County Conservation Foundation, Southwestern University, Georgetown, Texas. 37 pp.

Pierce, B. 2011b. Personal communication. Georgetown salamander site visit notes. October 4, 2011. U.S. Fish and Wildlife Service, Austin, Texas. 3 pp.

Randhir, T. and P. Ekness. 2009. Urbanization effects on watershed habitat potential: a multivariate assessment of thresholds and interactions. Ecohydrology 2: 88-101.

Schueler, T.R. 1991. Mitigating the adverse impacts of urbanization on streams: A comprehensive strategy for local government. Page 114-123 *in* Nonpoint Source Watershed Workshop: Nonpoint Source Solutions. Environmental Protection Agency Seminar Publication EPA/625/4-91/027. Washington, D.C.

Schueler, T.R. 1994. The importance of imperviousness. *In:* Schueler, T.R., and H.K. Holland, eds., The Practice of Watershed Protection, Watershed Protection Techniques Vol. 1(3). Center for Watershed Protection, Elliott City, Maryland, USA. pp. 100-111.

Schueler, T.R. and J. Galli. 1992. The environmental impacts of stormwater ponds. Watershed Restoration Sourcebook: collected papers presented at the conference "Restoring our home river—water quality and habitat in the Anacostia." 159-180.

Schueler, T.R., Fraley-McNeal, L, and K. Cappiella. 2009. Is impervious cover still important? Review of recent research. Journal of Hydrologic Engineering 14 (4): 309-315.

Shade, B.L., O'Donnell, L., Veni, G., and D. Johns . 2008. Pilot project: hydrogeologic delineation of habitat and management zones for the Jollyville Plateau salamander in the Austin, Texas area final report for August-November 2007. 35 pp.

Shaver, E., Maxted, J., Curtis, G., and D. Carter. 1995. Watershed protection using an integrated approach. Stormwater NPDES related monitoring needs: proceedings of an Engineering Foundation conference. 435-459.

Steedman, R.J. 1988. Modification and assessment of an index of biotic integrity to quantify stream quality in southern Ontario. Can. I. Fish. Aquat. Sci. 45: 492-501.

Stepenuck, K.F., Crunkilton, R.L., and L. Wang. 2002. Impacts of urban landuse on macroinvertebrate communities in southeastern Wisconsin streams. Journal of the American Water Resources Association 38 (4): 1041-1051.

Steuer, J.J., Stensvoid, K.A., and M.B. Gregory. 2010. Determination of biologically significant hydrologic condition metrics in urbanizing watersheds: an empirical analysis over a range of environmental settings. Hydrobiologia 654: 27-55.

Stranko, S.A., Hilderbrand, R.H., Morgan II, R.P., Staley, M.W., Becker, A.J., Roseberry -Lincoln, A., Perry E.S. & P.T. Jacobson. 2008. Brook Trout Declines with Land Cover and Temperature Changes in Maryland. North American Journal of Fisheries Management 28 (4): 1223-1232

SWCA Environmental Consultants. 2012. Technical response to USFWS proposed rule for endangered status for four central Texas salamanders and designation of critical habitat (77 FR 50768). Prepared for Williamson County Conservation Foundation. October 22, 2012. 99 pp.

Texas State Data Center. 2006. 2006 Population Estimates by County. [Accessed on October 30, 2012] http://txsdc.utsa.edu/Resources/TPEPP/Estimates/2006/2006_txpopest_county.csv

Texas State Data Center. 2009. 2009 Population Estimates by County. [Accessed on October 30, 2012] http://txsdc.utsa.edu/Resources/TPEPP/Estimates/2009/2009_txpopest_county.csv

U.S. Geological Survey. 2011. NHD Frequently Asked Questions. Updated Febuary 1, 2011. [Accessed September 24, 2012] http://nhd.usgs.gov/nhd_faq.html

Utz, R.M., Hilderbrand, R.H., and D.M. Boward. 2009. Identifying regional differences in threshold responses of aquatic invertebrates to land cover gradients. Ecological Indicators 9: 556-567.

Wang, L., J. Lyons, P. Kanehl, and R. Gatti. 1997. Influences of watershed land use on habitat quality and biotic integrity in Wisconsin streams. Fisheries 22 (6): 6-12.

Wang, L., J. Lyons, P. Kanehl, and R. Bannerman. 2001. Impacts of urbanization on stream habitat and fish across multiple spatial scales. Environmental Management 28 (2): 255-266.

Wenger, S.J., Roy A.H., Jackson, C.R., Bernhardt, E.S., Carter, T.L., Filoso, S., Gibson, C.A., Hession, W.C., Kaushal, S.S., Martí, E., Meyer, J.L., Palmer, M.A., Paul, M.J., Purcell, A.H., Ramírez, A., Rosemond, A.D., Schofield, K.A., Sudduth, E.B., and Christopher J. Walsh. 2009. Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. Journal of the North American Benthological Society 28 (4): 1080-1098.

Yoder, C.O. and R.J. Miltner. 1999. Assessing the status of aquatic life designed uses in urban and suburban watersheds. National conference on retrofit opportunities for water resource protection in urban environments in Chicago, IL on February 9-12, 1998: 16-28.