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Differences in Spring
Versus
Stream Fish Assemblages

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Abstract—Spring habitats often contain an array of uniquely adapted organisms. Their adaptations are correlated with environmental stability of these systems. Perturbations to these habitats may not only undermine biodiversity, but could have legal ramifications relative to the Endangered Species Act.

Springs have long been known to have a suite of environmental conditions that are sometimes drastically and sometimes subtly different from downstream habitats. Some of these factors include thermal stability in the springs and runs, differences in pH, conductivities, and fish assemblages. Many of these factors are different even when comparing spring versus downstream habitats as close as 100 m apart (Hubbs 2001). These differences are often most pronounced in relatively large springs and in these, different congeneric species often dominate in either the springs or in downstream areas. The spring-adapted species are also often unique to individual springs, having adapted to these specialized environments and are unable to compete with their downstream congener (Hubbs 2001). Even when unique forms are not present, the species composition of the assemblage inhabiting the spring remains different from that found downstream and this appears to be a general phenomenon, found in many localities for not only fishes, but other aquatic organisms (Hubbs and Hettler 1964; Emery 1967; Howell and Black 1976; Matthews et al. 1985; Robison and Buchanan 1988; Bowles and Arsuffi 1993; Chippindale et al. 1993; and summarized in Hubbs 2001).

I have worked on the specific differences between spring fishes and stream fishes and their physical and chemical environments for the past ten years. A preliminary study of eight spring and downstream riverine habitats (Hubbs 2001) showed this general pattern in springs in Texas. The present study expands this analysis to 15 spring systems (13 in Texas and 2 in Oklahoma) and further documents the differences between the fish assemblages and the environmental conditions found in these contrasting environments.

METHODS—The same procedures of using baited minnow traps at each location and taking readings with a Hydrolab Data Sonde instrument (calibrated monthly) at several sites within each location that are described in detail in Hubbs (2001) were used. In addition to enumerating the fishes captured in each minnow trap, the physical measurements taken were: temperature (°C), dissolved oxygen (mg/L), salinity (ppt), turbidity (NTU), pH, ammonia (mg/L NH_4), and nitrate (mg/L NO_3).

LOCALITIES SAMPLED—The locations for the Balmorhea springs (Phantom Cave and East Sandia springs), Diamond-Y Spring, Spring 4 Big Bend National Park, Anson Springs, Clear Creek Springs, San Marcos Springs, and Comal Springs are reported in Hubbs (2001). Subsequently I have samples at additional locations in Independence Creek (Chandler and Carolina springs), Devils River (Pecan Springs), San Felipe Creek, and Pinto Creek. I have also sampled from two Oklahoma spring systems (Poe and Blue River springs) (Fig. 1).

FIG. 1—Collection localities for 13 springs in Texas and 2 in Oklahoma. See text for locality information.

Independence Creek, Terrell County—The samples are from Chandler Springs to approximately 100 m downstream and Carolina Springs to approximately 2 km downstream.

Devils River, Val Verde County—Hubbs (2001) reported data from two springs in the Devils River, Finegan and Side Angle springs. In this study, findings are reported from the headsprings (Pecan Springs) of the Devils River downstream to Dolan Falls.

San Felipe Creek, Val Verde County—The samples are from the headsprings, to approximately 5 km downstream.

Pinto Creek, Kinney County—The samples are from the headsprings (where the federally threatened *Dionda diaboli* abounds) downstream to south of US 90 (where *Cyprinella lutrensis* abounds). Specific sites are detailed in Garrett et al. (2004).

Oklahoma—Two spring systems were sampled from that state. Blue River Springs from the headsprings downstream in the Blue River to east of Connerville (Johnston County) and Poe Springs from the headsprings in Buckhorn Creek downstream to the Wichita River (Murry County).

RESULTS AND DISCUSSION—The previous report (Hubbs 2001) includes 515,092 fish captures of 40 species, from eight spring systems; this report includes 1,137,289 fish of 71 species, from 15 spring systems (Appendices 1 through 3). Additionally, I have more than doubled the number of Hydrolab water chemistry samples (Appendix 4).

Additional sampling at the environments previously reported confirm and emphasize the distribution patterns reported earlier. In each of these localities, spring fish predominate upstream and stream fish dominate downstream. For example at Clear Creek, Menard County, Texas, the spring sample has six species (*Gambusia heterochir* is 92% and *G. affinis* is 0.09% of all fish) and the stream sample 100 m downstream has 12 species (no *G. heterochir* and *G. affinis* is 78% of all fish)(Appendix 3). The differences in fish diversity correlate with stenothermal temperatures in the spring (*SD* = 0.013°C) and eurythermal temperatures downstream (*SD* = 0.147°C). Three species (including *G. affinis*) are in common and three species (spring) and nine species (downstream) are different. In the springs, the temperature does not vary, but downstream it may change 1°C/hour (Hubbs, 2001). All fish present survive well under both thermal conditions in the laboratory, thus it is hypothesized that competitive interactions are responsible for the distribution. In many spring systems, pH is lower in the springs than downstream and is associated with temperature variation. Ammonia concentrations (typically lower in springs and higher downstream) also may be associated with temperature variation in some springs. These differences were consistent even though the average temperatures vary among springs between 15°C (Blue River Springs, Oklahoma) and 35°C (Spring 4, Big Bend National Park). Additionally, the variance in the chemical measurements was found to be less in spring sources than measurements taken downstream. Of the seven parameters measured, only pH and NO_3 had a tendency of greater variability overall in the headsprings than they did in downstream stations (Appendix 4).

There was considerable flow variation among springs. In the best two examples (Comal Springs and Phantom Cave Spring), the spring endemics were abundant when spring flow was high and stream species increased in relative abundance when spring flow was low. For example at Phantom Lake, served by Phantom Cave Spring, the spring *Gambusia* (*G. nobilis*) thrived in 1938 but none were taken from that lake for the last 15 years until the Phantom Cave Spring outflow recently exceeded the historic outflow of the last 20 years and *G. nobilis* made up 61% of the fish captured (Appendix 1). *Gambusia affinis* had dominated Phantom Lake for the past ten years (94% of all fish) but these died when the lake dried, thus could not compete with *G. nobilis* when the spring flows returned (Hubbs, 2001).

In the two springs sampled in Independence Creek, *G. geiseri*, introduced from the San Marcos spring-run, was the dominant fish captured (Appendix 2). Downstream, *Dionda episcopa* and *Lepomis macrochirus* were the most abundant species encountered, neither of which was abundant at the spring outlets. At the headwaters of the Devils River, *G. speciosa* accounted for almost all of the fish captured. Downstream, many more species were captured including a mixture of species commonly found in spring-run habitats as well as more stream-adapted species. The Devils River, in this section, contains numerous spring outflows, thus the species compositions reflect this circumstance. The San Felipe Springs similarly yielded almost only *G. speciosa.* Downstream, similar to the Devils River, abundance of other species increased.

In the Oklahoma springs examined, a dominant spring species is the darter *Etheostoma spectabile* and the stream darter is *Etheostoma radiosum* (Appendix 3). Oddly, in central Texas *E. spectabile* is the stream species and *Etheostoma lepidum* dominates in springs. *Gambusia affinis* was the dominant species in Poe Springs, and was the only species captured other than *E. spectabile.* In Blue River Springs, *Campostoma anomalum* was the dominant spring species and only moderately abundant downstream.

The spring samples have less biodiversity than the downstream samples at 12 of the spring systems (Appendices 1 through 3). At all but Phantom Cave, East Sandia and Diamond-Y, the downstream samples have more species than the spring samples. These three springs are unusual in that they do not drain into rivers or streams, but instead they disappear into the desert. They each had five or fewer downstream species (and

Gambusia hybrids) whereas most downstream localities had more than ten species.

Nevertheless, the spring populations contain the most unique species, and these are often federally endangered in this region. The difference in biodiversity is that most of the biota is adapted to changing conditions (primarily temperature) between summer and winter. Because springs do not greatly change with the seasons, many of these species cannot successfully compete against species which are adapted to these conditions.

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Appendix I—Relative abundance of fishes caught at spring systems and downstream. A designation of “tr” indicates less than 0.01%.

Species	Phantom Cave Spring		East Sandia Springs		Diamond-Y Spring		Spring 4 BBNP		Anson Springs	
	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream
Campostoma anomalum	-	-	-	-	-	-	-	-	0.01	0.05
Cyprinella lutrensis	-	-	-	-	-	-	-	33.27	-	-
Cyprinella venusta	-	-	-	-	-	-	-	-	-	2.03
Dionda episcopa	0.03	0.06	-	-	-	-	-	-	0.8	-
Notropis amabilis	-	-	-	-	-	-	-	-	-	76.19
Notropis volucellus	-	-	-	-	-	-	-	-	-	0.30
Pimephales vigilax	-	-	-	-	-	-	-	-	-	0.10
Astyanax mexicanus	9.03	30.36	0.20	1.38	-	-	-	4.10	2.07	-
Cyprinodon bovinus	-	-	-	-	0.02	1.14	-	-	-	-
Cyprinodon elegans	6.59	0.36	0.01	-	-	-	-	-	-	-
Cyprinodon hybrid	-	-	-	-	tr	0.01	-	-	-	-
Lucania parva	-	-	-	-	0.26	1.22	-	-	-	-

Appendix I (*continued*)

	Phantom Cave Spring		East Sandia Springs		Diamond-Y Spring		Spring 4 BBNP		Anson Springs	
Species	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream
Gambusia affinis	0.03	-	0.07	0.83	0.03	67.33	0.34	61.66	-	0.61
Gambusia gaigei	-	-	-	-	-	-	99.66	0.68	-	-
Gambusia geiseri	23.16	66.47	23.20	7.60	1.55	-	-	-	96.99	-
Gambusia nobilis	61.10	2.63	76.49	90.19	98.13	30.30	-	-	-	-
Gambusia hybrid	0.04	0.12	0.01	-	-	-	-	-	-	-
Poecilia latipinna	-	-	-	-	-	-	-	tr	-	-
Lepomis auritus	-	-	-	-	-	-	-	-	-	0.91
Lepomis cyanellus	0.02	-	0.02	-	-	-	-	-	0.01	-
Lepomis gulosus	-	-	-	-	-	-	-	-	-	0.15
Lepomis macrochirus	-	-	-	-	-	-	-	-	-	18.24
Lepomis megalotis	-	-	0.01	-	-	-	-	-	-	1.11
Micropterus salmoides	-	-	-	-	-	-	-	-	-	0.05
Etheostoma lepidum	-	-	-	-	-	-	-	-	0.12	-
Etheostoma spectabile	-	-	-	-	-	-	-	-	-	0.05

Appendix I (*continued*)

	Phantom Cave Spring		East Sandia Springs		Diamond-Y Spring		Spring 4 BBNP		Anson Springs	
Species	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream	Springs	Downstream
Cichlasoma cyanoguttatum	-	-	-	-	-	-	-	-	-	0.20
Oreochromis aureus	-	-	-	-	-	-	-	0.28	-	-
Total N	17,489	1,670	17,128	724	393,542	59,644	47,665	19,492	10,129	1,974
Number of Species	7	5	7	4	6	5	2	6	6	13

Appendix 2—Relative abundance of fishes cuaght at spring systems and downstream.

Species	Chandler Springs		Carolina Springs		Pecan Springs		San Felipe Springs		Pinto Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Lepisosteus osseus	-	-	-	-	-	0.14	-	-	-	-
Dorosoma cepedianum	-	-	-	0.01	-	-	-	-	-	-
Campostoma anomalum	-	-	-	-	-	1.54	-	-	-	-
Cyprinella lutrensis	-	-	-	0.85	-	-	-	-	-	32.23
Cyprinella proserpina	-	-	-	6.54	-	4.21	-	-	-	-
Cyprinella venusta	-	-	-	0.07	-	19.64	-	-	-	-
Cyprinus carpio	-	-	-	0.01	-	0.14	-	-	-	-
Dionda argentosa	-	-	-	-	0.25	6.59	1.06	28.53	-	-
Dionda episcopa	-	-	3.27	66.91	-	-	-	-	-	-
Dionda diaboli	-	-	-	-	-	-	0.02	3.20	4.98	-
Notropis amabilis	-	-	-	10.46	-	-	-	1.50	-	-
Notropis braytoni	-	-	-	0.01	-	-	-	-	-	-
Notropis stramineus	-	-	-	-	-	36.19	-	-	-	2.07
Moxostoma congestum	-	-	-	0.11	-	-	-	-	-	-

Appendix 2—*continued*

Species	Chandler Springs		Carolina Springs		Pecan Springs		San Felipe Springs		Pinto Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Astyanax mexicanus	-	-	22.15	0.79	-	-	9.35	4.46	14.63	1.65
Ictalurus lupus	-	-	-	0.34	-	-	-	-	-	-
Ictalurus natalis	-	-	-	-	-	-	0.03	-	-	-
Ictalurus punctatus	-	-	-	0.01	-	-	-	-	-	-
Pylodictis olivaris	-	-	-	0.01	-	-	-	-	-	0.21
Cyprinodon eximius	-	-	-	-	-	1.96	-	-	-	-
Cyprinodon hybrid	-	-	-	0.15	-	-	-	-	-	-
Fundulus zebrinus	-	-	-	0.14	-	-	-	-	-	-
Lucania parva	-	-	0.02	0.14	-	-	-	-	-	-
Gambusia affinis	-	0.30	-	6.93	-	-	-	-	-	-
Gambusia clarkhubbsi	-	-	-	-	-	-	0.26	5.56	-	-
Gambusia geiseri	100	-	73.75	3.79	-	-	-	-	-	-
Gambusia speciosa	-	-	-	-	99.75	4.77	89.25	56.08	74.72	34.30
Poecilia latipinna	-	-	-	-	-	-	-	-	-	3.93
Lepomis auritus	-	-	-	0.83	-	0.14	-	-	0.09	0.41

Appendix 2—*continued*

Species	Chandler Springs		Carolina Springs		Pecan Springs		San Felipe Springs		Pinto Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Lepomis cyanellus	-	22.15	-	0.27	-	-	-	0.03	-	-
Lepomis gulosus	-	-	-	-	-	-	-	-	-	0.62
Lepomis macrochirus	-	70.25	0.02	0.35	-	-	-	0.21	-	4.96
Lepomis megalotis	-	2.53	0.71	0.38	-	4.21	-	0.21	3.62	6.61
Lepomis microlophus	-	-	-	-	-	-	-	-	-	0.21
Micropterus dolomieu	-	-	-	-	-	0.28	-	-	-	-
Micropterus salmoides	-	4.75	-	0.18	-	0.28	-	-	-	1.65
Etheostoma grahami	-	-	0.02	0.41	-	-	0.02	0.11	-	-
Cichlasoma cyanoguttatum	-	-	0.05	0.3	-	19.78	0.02	0.08	1.97	11.16
Oreochromis aureus	-	-	-	-	-	0.14	-	0.03	-	-
Total N	1,046	316	12,942	13,517	799	713	17,578	3,723	2,290	484
Number of Species	1	5	8	24	2	15	8	12	6	13

Appendix 3—Relative abundance of fishes cuaght at spring systems and downstream. A designation of "tr" indicates less than 0.01%.

Species	Clear Creek Spring		San Marcos Spring		Comal Springs		Poe Springs		Blue River Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Campostoma anomalum	-	-	-	3.01	-	-	-	18.31	71.45	6.77
Cyprinella lutrensis	-	-	-	0.03	-	-	-	-	-	-
Cyprinella venusta	-	-	-	29.09	-	-	-	-	-	2.60
Dionda episcopa	7.36	7.68	-	-	-	-	-	-	-	-
Dionda nigrotaeniata	-	-	25.58	0.14	-	-	-	-	-	-
Luxilis chrysocephalis	-	-	-	-	-	-	-	-	-	16.14
Lythrurus fumeus	-	-	-	-	-	-	-	-	-	0.19
Lythrurus umbratilis	-	-	-	-	-	-	-	-	-	0.37
Nocomis asper	-	-	-	-	-	-	-	-	-	0.83
Notemigonus crysoleucas	-	-	-	0.03	-	-	-	-	-	-
Notropis amabilis	-	-	-	6.53	-	0.35	-	-	-	-
Notropis boops	-	-	-	-	-	-	-	-	-	7.42
Notropis stramineus	-	-	-	-	-	-	-	-	-	0.74
Notropis suttkusi	-	-	-	-	-	-	-	-	-	5.84
Notropis volucellus	-	-	-	1.63	-	0.12	-	-	-	-

Appendix 3—*continued*

Species	Clear Creek Spring		San Marcos Spring		Comal Springs		Poe Springs		Blue River Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Phoxinus erythrogaster	-	-	-	-	-	-	-	-	3.00	-
Pimephales notatus	-	-	-	-	-	-	-	-	-	0.27
Pimephales vigilax	-	-	-	0.95	-	-	-	-	-	-
Minytrema melanops	-	-	-	-	-	-	-	-	-	0.09
Moxostoma congestum	-	-	-	0.33	-	-	-	-	-	-
Moxostoma erythrurum	-	-	-	-	-	-	-	-	0.13	1.21
Astyanax mexicanus	-	-	0.15	0.11	tr	0.59	-	-	-	-
Ictalurus melas	tr	-	-	-	-	-	-	-	-	0.28
Ictalurus natalis	tr	-	-	-	-	-	-	1.41	-	-
Hypostomus sp.	-	-	-	0.05	-	-	-	-	-	-
Lucania parva	-	0.77	-	-	-	-	-	-	-	-
Gambusia affinis	0.09	78.28	0.02	41.59	0.04	42.64	72.97	12.68	9.13	5.75
Gambusia geiseri	-	-	70.43	1.27	93.31	44.29	-	-	-	-
Gambusia heterochir	92.33	-	-	-	-	-	-	-	-	-
Gambusia hybrid	0.02	-	-	-	-	-	-	-	-	-

Appendix 3—*continued*

Species	Clear Creek Spring		San Marcos Spring		Comal Springs		Poe Springs		Blue River Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Poecilia formosa	-	-	tr	2.28	tr	-	-	-	-	-
Poecilia latipinna	-	-	3.34	7.78	6.59	2.24	-	-	-	-
Lepomis auritus	-	0.17	0.01	0.03	-	-	-	-	-	-
Lepomis cyanellus	-	0.02	-	0.03	-	0.47	-	-	-	-
Lepomis gulosus	-	0.66	0.01	0.08	-	-	-	-	-	-
Lepomis humilis	-	-	-	0.03	-	-	-	-	-	-
Lepomis macrochirus	-	0.16	0.03	0.95	-	2.00	-	-	-	9.74
Lepomis megalotis	-	2.64	0.06	1.30	-	1.77	-	-	-	0.28
Lepomis microlophus	-	0.13	tr	0.16	-	-	-	-	-	-
Lepomis punctatus	-	0.36	0.35	0.05	tr	3.18	-	-	-	-
Micropterus dolomieu	-	-	-	0.19	-	-	-	-	-	0.37
Micropterus salmoides	-	0.81	0.01	0.43	tr	0.59	-	4.23	-	0.19
Etheostoma fonticola	-	-	0.02	-	tr	-	-	-	-	-
Etheostoma lepidum	0.19	0.32	-	-	-	-	-	-	-	-
Etheostoma microperca	-	-	-	-	-	-	-	-	0.13	0.19

Appendix 3—*continued*

Species	Clear Creek Spring		San Marcos Spring		Comal Springs		Poe Springs		Blue River Springs	
	Springs	Dwnstrm*	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm	Springs	Dwnstrm
Etheostoma radiosum	-	-	-	-	-	-	-	-	0.13	0.19
Etheostoma spectabile	-	-	-	1.60	-	-	27.03	63.38	16.17	9.83
Etheostoma hybrid	-	-	-	-	-	-	-	-	-	0.28
Percina caprodes	-	-	-	0.03	-	-	-	-	-	0.09
Percina sciera	-	-	-	0.08	-	-	-	-	-	-
Cichlasoma cyanoguttatum	-	-	-	0.22	0.04	1.77	-	-	-	-
Total N	232,102	6,325	86,033	3,688	183,474	849	37	71	767	1,078
Number of Species	6	12	14	29	9	12	2	5	6	23

Appendix 4—Average values (standard deviation) of environmental variables for springs at localities in Texas and Oklahoma.

	Temperature (°C)				Dissolved O_2 (mg/L)			
	n	spring	n	downstream	n	spring	d	downstream
Phantom Cave Spring	263	22.911 (0.541)	59	20.110 (1.344)	263	3.814 (0.069)	59	6.909 (7.836)
East Sandia Springs	182	20.723 (0.118)	2	20.356 (0.000)	182	7.496 (0.190)	2	7.795 (0.000)
Diamond-Y Spring	145	20.003 (0.069)	365	18.776 (0.293)	145	3.972 (0.069)	365	8.068 (0.203)
Spring 4 (BBNP)	6	34.940 (0.089)	744	21.867 (0.141)	6	4.920 (0.496)	744	6.133 (0.068)
Anson Springs	27	18.897 (0.025)	202	18.727 (0.327)	27	5.673 (0.025)	202	5.681 (0.137)
Chandler & Carolina Springs	52	21.458 (0.063)	27	18.700 (1.901)	52	6.268 (0.003)	27	7.414 (0.413)
Pecan Springs	17	23.234 (0.367)	86	27.165 (0.097)	17	5.582 (0.338)	86	6.596 (0.150)
San Felipe Springs	54	23.603 (0.059)	169	23.487 (0.071)	54	5.019 (0.249)	169	4.659 (0.405)
Pinto Springs	26	24.270 (0.160)	45	28.344 (0.318)	26	5.070 (0.002)	45	6.050 (0.297)
Clear Creek Springs	663	20.836 (0.013)	399	25.387 (0.147)	558	6.741 (0.092)	296	5.149 (1.631)
San Marcos Springs	349	21.637 (0.031)	306	21.659 (0.174)	349	4.249 (0.032)	306	3.776 (0.088)
Comal Springs	197	23.160 (0.038)	230	22.150 (0.077)	197	5.685 (0.099)	230	5.974 (0.099)
Poe Springs, OK	50	16.897 (0.070)	39	14.100 (0.205)	50	6.045 (0.266)	39	7.581 (0.483)
Blue River Springs, OK	5	14.514 (3.114)	56	15.219 (1.262)	5	7.808 (0.877)	56	6.293 (0.349)

Appendix 4—*continued*

	Salinity (ppt)				Turbidity (NTU)			
	n	spring	n	downstream	n	spring	d	downstream
Phantom Cave Spring	263	1.839 (0.000)	59	5.241 (0.841)	263	2.798 (0.202)	59	27.149 (7.199)
East Sandia Springs	182	20.723 (0.118)	2	2.170 (0.000)	182	26.212 (4.898)	2	6.000 (0.000)
Diamond-Y Spring	145	3.744 (0.032)	365	11.247 (0.151)	145	24.166 (5.804)	365	36.299 (3.002)
Spring 4, Big Bend National Park	6	0.066 (0.000)	744	0.566 (0.002)	6	2.185 (1.642)	744	31.447 (2.091)
Anson Springs	27	0.288 (0.002)	202	0.293 (0.001)	27	5.305 (3.230)	202	50.518 (6.801)
Chandler & Carolina Springs	52	0.408 (0.064)	27	0.264 (0.001)	52	6.946 (0.418)	27	186.80 (36.635)
Pecan Springs	17	0.209 (0.002)	86	0.162 (0.014)	17	43.98 (27.930)	86	11.865 (5.148)
San Felipe Springs	54	0.233 (0.002)	169	0.243 (0.001)	54	26.496 (8.166)	169	16.375 (2.796)
Pinto Springs	26	0.240 (0.225)	45	0.266 (0.001)	26	50.564 (27.026)	45	90.959 (27.957)
Clear Creek Springs	558	0.301 (0.001)	296	0.295 (0.003)	558	4.043 (0.734)	296	36.833 (5.400)
San Marcos Springs	349	0.241 (0.000)	306	0.030 (0.010)	349	0.000 (0.238)	306	44.814 (6.873)
Comal Springs	197	0.262 (0.001)	230	0.269 (0.001)	197	0.950 (0.184)	230	12.746 (2.710)
Poe Springs, OK	-	-	-	-	50	19.798 (9.667)	39	40.249 (16.236)
Blue River Springs, OK	-	-	-	-	5	81.280 (51.967)	56	0.833 (6.181)

Appendix 4—*continued*

	pH				NH4 (mg/L)			
	n	spring	n	downstream	n	spring	d	downstream
Phantom Cave Spring	263	7.454 (0.398)	59	6.924 (0.325	263	2.430 (0.340)	59	1.356 (0.161)
East Sandia Springs	182	7.156 (0.016)	2	7.195 (0.001)	182	2.031 (0.120)	2	1.845 (0.279)
Diamond-Y Spring	145	6.903 (0.019)	365	7.071 (0.017)	145	2.526 (0.143)	365	8.245 (0.441)
Spring 4, Big Bend National Park	6	7.088 (0.034)	744	7.712 (0.008)	6	3.005 (0.338)	744	1.758 (0.024)
Anson Springs	27	6.677 (0.022)	202	7.441 (0.009)	27	0.127 (0.104)	202	0.150 (0.007)
Chandler & Carolina Springs	52	7.660 (0.046)	27	8.376 (0.056)	52	0.246 (0.017)	27	0.361 (0.044)
Pecan Springs	17	7.129 (0.074)	86	8.697 (0.025)	17	0.599 (0.090)	86	2.000 (0.036)
San Felipe Springs	54	7.476 (0.036)	169	7.640 (0.013)	54	0.244 (0.012)	169	1.400 (0.002)
Pinto Springs	26	7.242 (0.300)	45	7.766 (0.022)	-	-	-	-
Clear Creek Springs	558	6.141 (0.029)	296	9.691 (0.199)	558	0.294 (0.022)	296	1.018 (0.042)
San Marcos Springs	349	7.296 (0.012)	306	8.010 (0.015)	349	0.130 (0.008)	306	0.262 (0.234)
Comal Springs	197	7.377 (0.012)	230	7.873 (0.017)	197	0.177 (0.012)	230	0.199 (0.013)
Poe Springs, OK	50	6.912 (0.195)	39	8.389 (0.426)	50	0.774 (0.306)	39	0.356 (0.770)
Blue River Springs, OK	5	7.040 (0.302)	56	9.243 (1.001)	5	0.346 (0.185)	-	-

Appendix 4—*continued*

	NO3 (mg/L)			
	n	spring	n	downstream
Phantom Cave Spring	263	11.535 (0.205)	59	21.700 (1.969)
East Sandia Springs	182	2.244 (0.561)	2	2.3800 (0.036)
Diamond-Y Spring	145	25.032 (1.537)	365	17.635 (0.683)
Spring 4, Big Bend National Park	6	6.567 (1.459)	744	4.762 (0.114)
Anson Springs	27	14.468 (2.825)	202	17.090 (1.355)
Chandler & Carolina Springs	52	0.146 (0.212)	27	3.012 (2.052)
Pecan Springs	17	3.959 (0.609)	86	2.000 (0.058)
San Felipe Springs	54	3.744 (0.177)	169	1.688 (0.037)
Pinto Springs	-	-	-	-
Clear Creek Springs	558	7.509 (0.318)	296	8.295 (0.002)
San Marcos Springs	349	4.938 (0.369)	306	6.856 (0.476)
Comal Springs	197	8.297 (0.599)	230	8.397 (0.477)
Poe Springs, OK	50	0.823 (0.100)	39	0.348 (0.028)
Blue River Springs, OK	5	0.739 (0.075)	-	-