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Barton Springs Salamanders, Spring Discharge and Dissolved Oxygen
An Update to DR-07-07 BSS&ABS Salamander Data Report 2006 and SR-04-06 Some Water Quality Threats to the BBS at Low Flows

Martha A. Turner, P.E.
SR-09-02
May 2009

Abstract
An evaluation of salamander counts, spring flow rates, and dissolved oxygen concentrations was completed to update previously collected data. Originally, this evaluation was used to recommend a pumping limit for sustainable yield to the Barton Springs Edwards Aquifer Conservation District. The primary purpose of the current evaluation was to verify correlations between flow, dissolved oxygen, and surface count data of the endangered Barton Springs Salamander. Significant correlations provide the statistical basis for setting thresholds for Barton Springs flows related to a water quality parameter commonly used in aquatic life support. The pattern previously observed in Barton Springs Pool, with salamander counts increasing during extended periods of declining flow and then decreasing at very low flows, was confirmed. The relationships among the combined Barton Springs discharge and DO in Barton, Eliza and Old Mill) were also confirmed with the addition of three more years of data that include values in the low range. Correlations were also found with DO and surface counts. The peak correlation between counts and DO was found for a lag of 6 months.

Introduction
Analyses done on data collected between 1993 and the fall of 2006 are updated with new information collected through April of 2009. Survey methods were improved in 2003, so salamander counts before and after that time are not necessarily comparable. In addition, habitat reconstruction in 2003 improved the ecology and flow regime in Eliza Spring, which is expected to promote higher dissolved oxygen (DO) concentrations in that site (Giller and Malmqvist 1998, Spellman and Drinan 2001, Kalff 2002).

In most cases salamander counts and DO data were collected on the same date. On those dates for which we have counts but no coinciding DO, we used DO measured within three days before or after the counts, or DO measured within three weeks of the count date if DO differed by less than 0.25 mg/L during that time period.

Discharge values used here are U.S. Geological Survey data for combined springs in the Barton Springs complex (Eliza, Old Mill, Barton Springs Pool, and Upper Barton). In this data report, low discharge refers to combined Barton Springs discharge values that are ≤ 30 cfs, high discharge refers to values ≥ 50 cfs. Droughts are defined as those periods when combined Barton Springs discharge is ≤ 25 cfs.

Combined Barton Springs Discharge and Salamander Counts

- Salamander counts reached all time highs in the first few months in 2008 (except in Old Mill Spring).
- Minimum salamander counts in Barton Springs Pool during the latest drought have thus far remained higher than in previous droughts. However the lowest counts typically occur after discharge has started to increase at the end of a drought, so we have probably not yet reached the lowest counts for the current drought.
Table 1. Minimum Counts (down from previous maximum count) in Barton Springs Pool and Eliza Spring in Droughts

<table>
<thead>
<tr>
<th>Drought Year</th>
<th>Barton Min. Count</th>
<th>Eliza Min. Count</th>
<th>Minimum Discharge ≤ 25 cfs</th>
<th># Days with</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>7 (45)</td>
<td>1 (29)</td>
<td>17</td>
<td>154</td>
<td>Feb96 - Sep96</td>
</tr>
<tr>
<td>2000</td>
<td>3 (78)</td>
<td>1 (12)</td>
<td>17</td>
<td>112</td>
<td>Feb00 - Oct00</td>
</tr>
<tr>
<td>2006</td>
<td>1 (300)</td>
<td>216 (738)</td>
<td>19</td>
<td>132</td>
<td>Jul06 - Dec06</td>
</tr>
<tr>
<td>2008/2009</td>
<td>20 (447)</td>
<td>69 (1234)</td>
<td>14</td>
<td>361+</td>
<td>Jul08 - ?</td>
</tr>
</tbody>
</table>

(7/30/09)

- In Eliza Spring, however, the counts are lower now than they were in the 2006 drought, the only other drought since the habitat improvement in 2003.
- In Old Mill Spring and Upper Barton Spring the counts have dropped to zero in all droughts.
- The pattern previously observed in Barton Springs Pool, with salamander counts increasing during extended periods of declining flow and then decreasing at very low flows, was confirmed (Figure 1). This can also be observed in Eliza and Old Mill Springs in the fall of 2005 and the spring of 2008 (Figures 2, 3). However there are also declines in the counts when flows remain high. For example, consider the winter of 2005 when the combined discharge from Barton Springs remained above average for many months but counts decreased in all four springs (Figures 1-4). The apparent boom and bust nature of salamander abundance suggests that other factors, as well as low discharge and DO, are involved. For example, flow velocity directly affects the ecological character of a spring-fed stream (Cushing and Allan 2001, Wetzl 2001), along with dissolved oxygen concentrations (Giller and Malmqvist 1998, Wetzl 2001 and references therein) and therefore salamander health (Duellman and Trueb 1986, Hillman et al. 2009). Ecological effects of variation in flow velocity in salamander habitat are not easily extrapolated from discharge values estimated from rating curves that are based on constant width and depth of channel, as are the U.S.G.S. values for Barton Springs. The effects of stormwater runoff, flooding, sustained high flows, excess sediment, and prey availability on salamander habitat and abundance are also the factors that could be investigated. Although discharge provides a valuable measure of flow from the springs combined, investigation of how other factors influence salamander abundance within and among sites is necessary to fully understand population dynamics of *E. sosorum*. 
Figure 1.
Combined Barton Springs Discharge and Adult+Juvenile Salamander Count at Barton Springs
Straight Line Fill = Adults, Hatched = 1 to 2 In., Vertical Line = < 1 In.

Figure 2.
Combined Barton Springs Discharge and Adult+Juvenile Salamander Count at Eliza Springs
Straight Line Fill = Adults, Hatched = 1 to 2 In., Vertical Line = < 1 In.
Combined Barton Springs Discharge and Adult+Juvenile Salamander Count at Old Mill Springs

Straight Line Fill = Adults, Hatched = 1 to 2 In., Vertical Line = < 1 In.

Figure 3.

Combined Barton Springs Discharge and Adult+Juvenile Salamander Count at Upper Barton Springs

Straight Line Fill = Adults, Hatched = 1 to 2 In., Vertical Line = < 1 In.

Figure 4.
Combined Barton Springs Discharge and DO

The relationships among the combined Barton Springs discharge and DO in Barton, Eliza and Old Mill (see SR-07-07) were confirmed with the addition of three more years of data that include values in the low range. Plots of DO in each spring site and combined discharge over from 2003-2009 suggest coincident patterns, and regressions of all DO data on discharge (1993 or 1996 – 2009), including both grab samples and Datasonde monitoring, demonstrate statistically significant relationships (Figures 5 – 7). Coefficients changed slightly in the regression equations with the addition of recent three years of data including more low discharge values (Table 2). Table 3 lists the expected combined discharge at the lethal concentrations for 5, 10, 15, and 50 % mortality rate for *E. nana*, surrogate for *E. sosorum* (lethal concentrations from Poteet and Woods, 2007). It should be noted that the effect of any of these levels of DO on the population of salamanders in a particular spring site depends on the extent of time that dissolved oxygen remains at these levels and the initial number of salamanders.

Table 2. Regression equation for DO at three springs and the combined discharge of the four Barton Springs

<table>
<thead>
<tr>
<th>Spring</th>
<th>Dates</th>
<th>Equation</th>
<th>Pr&gt;F</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barton</td>
<td>1993-2009</td>
<td>DO=−0.25268+1.50637*Ln(Discharge)</td>
<td>&lt;0.0001</td>
<td>.66</td>
</tr>
<tr>
<td>Eliza</td>
<td>1996-2009</td>
<td>DO=0.14418+1.46046*Ln(Discharge)</td>
<td>&lt;0.0001</td>
<td>.63</td>
</tr>
<tr>
<td>Old Mill</td>
<td>1996-2009</td>
<td>DO=-4.85566+2.43535*Ln(Discharge)</td>
<td>&lt;0.0001</td>
<td>.74</td>
</tr>
</tbody>
</table>

Table 3. Discharge at Barton Springs (cfs) Predicted Dissolved Oxygen (mg/L) at Barton Springs Lethal Concentration

<table>
<thead>
<tr>
<th>Discharge at Barton Springs (cfs)</th>
<th>Predicted Dissolved Oxygen (mg/L) at Barton Springs</th>
<th>Lethal Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.7</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>16.8</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>15.9</td>
<td>3.91</td>
<td>LC5</td>
</tr>
<tr>
<td>11.4</td>
<td>3.41</td>
<td>LC10</td>
</tr>
<tr>
<td>9.4</td>
<td>3.12</td>
<td>LC15</td>
</tr>
<tr>
<td>8.7</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>2.12</td>
<td>LC50</td>
</tr>
<tr>
<td>4.5</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discharge at Barton Springs (cfs)</th>
<th>Predicted Dissolved Oxygen (mg/L) at Eliza Spring</th>
<th>Lethal Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>13.9</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>13.1</td>
<td>3.91</td>
<td>LC5</td>
</tr>
<tr>
<td>9.3</td>
<td>3.41</td>
<td>LC10</td>
</tr>
<tr>
<td>7.6</td>
<td>3.12</td>
<td>LC15</td>
</tr>
<tr>
<td>7.0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>2.12</td>
<td>LC50</td>
</tr>
<tr>
<td>3.6</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Table 3 (continued)

<table>
<thead>
<tr>
<th>Discharge at Barton Springs (cfs)</th>
<th>Predicted Dissolved Oxygen (mg/L) at Old Mill Spring</th>
<th>Lethal Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>57.2</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>38.0</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>36.6</td>
<td>3.91</td>
<td>LC5</td>
</tr>
<tr>
<td>29.8</td>
<td>3.41</td>
<td>LC10</td>
</tr>
<tr>
<td>26.4</td>
<td>3.12</td>
<td>LC15</td>
</tr>
<tr>
<td>25.2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>17.5</td>
<td>2.12</td>
<td>LC50</td>
</tr>
<tr>
<td>16.7</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8 shows the differences between the previous (2006) equations and the current ones at low flows. Slightly higher DO is predicted at low discharge using the more recent coefficients than was predicted in 2006.

Figure 9 shows the comparison between predicted DO at the three sites using the current regression equations. At low flows, DO is predicted to be highest at Eliza, slightly lower at Barton Springs Pool and 2 to 3 mg/L lower at Old Mill.
Figure 5.

**Barton Springs 1993–2009 Data**

DO = $-0.25368 + 1.50697 \times \ln(\text{Discharge})$

$Pr > F < 0.0001$ and $R^2 = 0.6584$

**Eliza Spring**
Old Mill Spring 1996–2009 Data

\[ \text{DO} = -4.85566 + 2.48585 \times \text{Ln(Discharge)} \]
\[ P > F < 0.0001 \text{ and } R^2 = 0.7447 \]

Figure 7.
Figure 8.

Figure 9
DO and Salamander Counts

Plots were examined (Figure 10) to see if there is an obvious pattern of variation in salamander counts and DO in Barton, Eliza and Old Mill using the available data. It is apparent that the variation in counts is high for the higher DO concentrations, suggesting that other factors are involved. Aquatic amphibian species are known to vary in tolerance for both low and high DO (Hillman et al. 2009), a species is typically adapted to an ideal range of concentrations that often reflect the physical and chemical characteristics of its habitat (Duellman and Trueb 1986). While a DO concentration of 3.91 mg/L in water at 21°C corresponds with oxygen saturation of 44%, it causes only 5% mortality in *E. nana* in the laboratory (Woods and Poteet 2006). Since Edwards Aquifer *Eurycea* inhabit waters that are naturally undersaturated with oxygen, these results suggest that these species are adapted to a lower ideal range of oxygen saturations. They also suggest that unusually high DO concentrations may exert direct or indirect sublethal effects on Edwards *Eurycea*. In addition, other factors associated with high discharge, such as stormwater runoff, flooding, sustained high flows, excess sediment, and prey availability, influence the ecological and chemical composition of salamander habitat and are therefore, also likely to influence salamander counts. Since we do not have data on the direct effects of high DO on *E. nana* or *E. sosorum*, and it is not clear how multiple factors may interact at high discharges, it was decided to focus here on the effects of the range of DO concentrations where direct negative effects are expected and have been demonstrated (Woods and Poteet 2006).

We examined the effects of low DO concentrations in two ways, first by only considering the data where DO levels were less than the LC1 or 5.03 mg/L, and second by examining the relationship in Barton Springs Pool and Eliza Spring with low DO levels six months earlier.

**DO < LC1 = 5.03 mg/L and Salamander Counts**

While linear relationships between DO and counts are significant, it is apparent from consideration of the plots that a linear relationship is not the best fit to the data. Curve Expert 3.1 was used to compare non-linear regression of DO versus the total salamander counts with DO as the independent variable and count as the dependent variable. Power curves were chosen to fit the data based on biological reasonableness, correlation coefficients, standard errors and the consistency among the coefficients for the different springs (Table 4, Figure 11). Logistic and modified exponential equations were also considered, but were rejected based on problems with the fit at Barton Springs due to apparent outliers. The choice of what type of non-linear equation to fit should be reconsidered when we have gathered more data. It is important to remember that the fitted curves must not be extended to predict counts for DO concentrations greater than the LC1 or 5.03 mg/L.

Power curves were also fit separately to juveniles and adults. The patterns were the same, with no major differences the goodness of the fit, or type of curve that is appropriate.
Figure 10.
Table 4. Regression equations for DO versus salamander counts when DO < LC1=5.03 mg/L.

<table>
<thead>
<tr>
<th>Spring</th>
<th>Dates</th>
<th>Equation: ( y=ax^b )</th>
<th>S</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barton</td>
<td>1993-2009</td>
<td>Count= 0.185*DO(^{1.30})</td>
<td>43.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Eliza</td>
<td>1996-2009</td>
<td>Count= 0.54*DO(^{4.49})</td>
<td>190.4</td>
<td>0.64</td>
</tr>
<tr>
<td>Old Mill</td>
<td>1996-2009</td>
<td>Count= 0.00436*DO(^{4.58})</td>
<td>0.134</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Figure 11
In Barton Springs Pool and Eliza Spring, a typically observed pattern is that both discharge and DO peak and then start to decline, with the decline in DO coming slightly after the decline in discharge. As DO and discharge are declining, salamander counts increase for a while and then decline also. The salamander counts continue to decline after the flows have reached their lowest value and begin to increasing again. The peak correlation between counts and DO was found for a lag of 6 months. A possible explanation is that the effects of chronic sublethal low DO on reproduction could be observed within 6 months in declines in counts of juveniles and subsequently in counts of adults. In Figure 12 the relationship between three DO levels; <LC5, LC5-LC1 and >LC1 and counts is shown. Notice particularly that the proportion of juveniles increases as the DO six months earlier increases. In Eliza Spring the percent of the count that is in the juvenile size class is 13% for DO six month earlier less than 3.91 (LC5) and 31% for DO six month earlier greater than 5.03 (LC5).
Mean Salamander Counts in Barton Springs Pool 1993–2009

Mean Salamander Counts in Eliza Spring 1996–2009

Figure 12
Literature Cited


