Title

Morphology, hydrology, and water quality of two vernal pools in Madera County, California

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Morphology, hydrology, and water quality of two vernal pools in Madera County, California

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ABSTRACT

Vernal pools are unique ecosystems that are under great threat from urban and agricultural expansion. Many of the biological processes critical for successful construction and restoration of vernal pools, including those that allow fairy shrimp cysts to hatch, are not well understood. To further research on vernal pool functioning, we conducted a one-month study of two vernal pools on the Caltrans Mitigation site in Madera County, California. We placed data-logging temperature sensors along the long axis at the bottom of each vernal pool; over three site visits we also collected water quality data (temperature by a second method, pH, conductivity, and dissolved oxygen) at these same points. In addition, we collected data on aquatic community, pool morphology and hydrology, and rainfall on the site. Although other studies have recognized that direct precipitation influences the morphological characteristics of vernal pools in general, we found these two individual vernal pools to be quite different in both their morphology and hydrology in response to precipitation. One pool increased five-fold in surface area and only gradually in depth, while the other pool increased 1.5-fold in depth while increasing, then decreasing in surface area over the study period. We found that the two pools support different aquatic communities, most likely based on these differences in habitat. Additionally, we found that a spatial temperature distribution existed in one vernal pool by analysis of variance (temperature sensors from second pool will be retrieved once pool dries). By regression analysis we found that "position" (distance from the pool edge along long axis) explains trends in temperature and pH better than "depth" (water level above each sensor, from pool bottom to surface). Conductivity and dissolved oxygen showed no significant trends in regards to position or depth. The existence of microhabitats within a vernal pool may explain our findings of spatial temperature stratification and the stronger relationships between water chemistry variables and position (versus depth). There is ample support in the literature for microhabitats in lotic systems, whereas this is a new finding for vernal pools and as such, warrants further study especially as it relates to the ecology of natural and mitigated vernal pools

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Introduction

Vernal pools are ephemeral wetland habitats with great ecological and evolutionary value because they support a rare and endemic flora and fauna. Over 90% of vernal pools in California have been lost to urban expansion and agricultural conversion, and the rate of this loss is accelerating (Dugan 1993; USEPA 2005). To address the problem, the EPA has specified that mitigation of wetland loss is an acute goal (Federal Register 1995). Mitigation through careful restoration, enhancement, and/or creation of replacement habitat is the goal of wetland conservation and protection. However, vernal pool creation will not succeed if complex ecological processes underlying the biology of sensitive wetland species are not well understood. For example, newly created pools are inoculated with fairy shrimp cysts (resting embryos), yet the environmental factors that trigger hatching of these cysts are poorly understood. In pools with unsuitable hatching conditions, the cysts cannot hatch and form viable populations (B. Helm, Helm Biological Consulting, personal communication, October 2005). The physical and chemical parameters of vernal pools, such as spatial gradients of temperature and variation in rainfall, have not been well studied in relation to cyst hatching.

From a review of various studies on potential hatching stimuli for fairy shrimp cysts, no unified conclusions can be been drawn. Several studies have implicated water quality parameters as possible hatching stimuli including: temperature (Eriksen and Belk 1999), oxygen (Moore 1963; Broch 1965; Brown and Carpelan 1971), salinity (Horne 1967; Brown and Carpelan 1971; Daborn 1975), conductivity (Theiry 1975), and pH and carbon dioxide (Mossin 1986). However, most studies of freshwater anostraca (fairy shrimp) were not made in California, but in humid regions where changes in salinity are negligible and where regulation of hatching is predominantly by oxygen concentration.

Hydrologic factors could also regulate cyst hatching through their influence on water quality parameters, pool morphology and ponding. In particular, ponding characteristics, including the duration of inundation and timing of desiccation, directly regulate the composition of vernal pool plant communities (Keeley and Zedler 1998) with associated influences on the entire vernal pool system. While several factors may influence ponding characteristics, such as surface runoff, intermittent streamflow, groundwater, and overbank flooding from adjacent water bodies (Colburn 2004), direct precipitation has been found to be the most important factor (Bauder 2005; Keeley and Zedler 1998; Hanes and Stromberg 1998; Vollmar 2002).

Objectives

Our study objective was to determine whether spatial temperature gradients exist along the bottom of vernal pools, how these patterns relate to rainfall, and how both of these parameters may be related to other physical, chemical and biological factors. This research question is one that we could tackle in a short research project, set within the larger ecological and conservation problem of what factors influence fairy shrimp cyst hatching in vernal pools.

Methods

Study site selection

We evaluated two pools in a 100-acre Caltrans Mitigation Bank site in Madera County, California (Figure 1). A Mediterranean climate, with rainy winters and dry, hot summers, characterizes this region. The site is situated on the alluvial terraces of the Central Valley, one of the three primary landscape types that generate vernal pools in California; the other two are coastal terraces in southern California and eroded lava flows (Keeley and Zedler 1998).

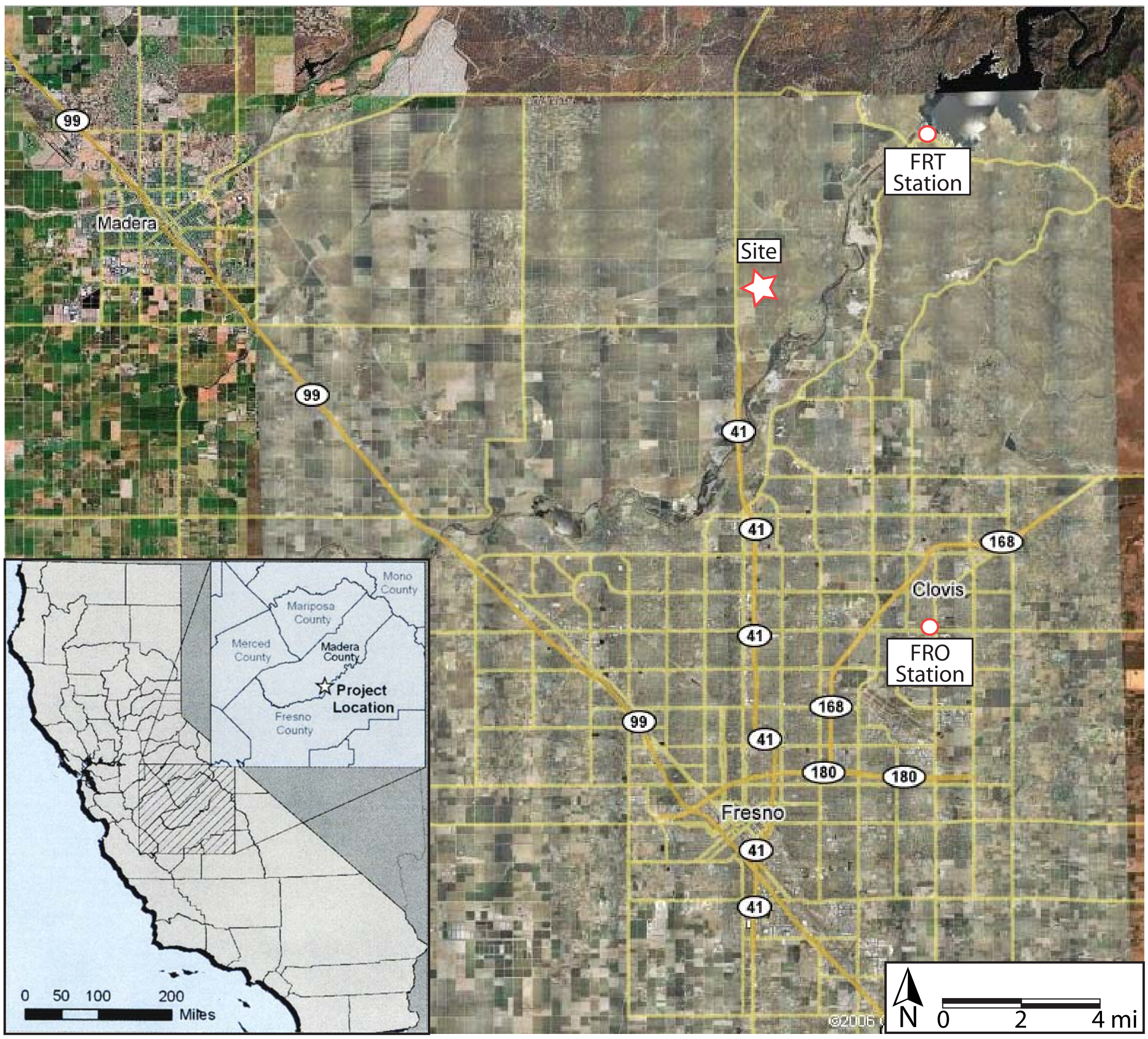


Figure 1. Study site is located in Madera County, California, ten miles north of Fresno. Precipitation data was gathered from nearby rain gauge stations: Friant Dam (FRT), located approximately six miles from study site; and Fresno WB AP (FRO), located approximately thirteen miles from study site.

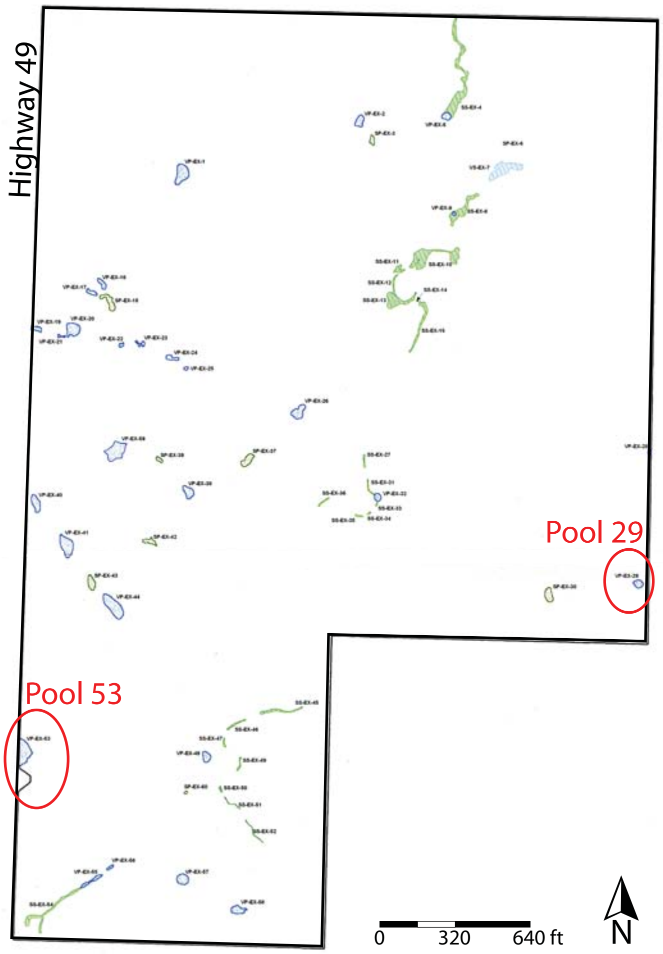


Figure 2. There are 60 delineated wetlands and vernal pools on the study site; research was conducted on Pool 29 and Pool 53.

The site has 60 delineated wetland areas; we found six vernal pools holding water during a preliminary site visit conducted on February 10, 2006. Undulating grasslands grazed by cows dominate the landscape with wetlands and vernal pools distributed throughout the site. We conducted our research on Pool 29, a natural vernal pool located adjacent to a fence on the eastern edge of the site, and on Pool 53, an artificial vernal pool located adjacent to Highway 49 on the western edge of the site (Figure 2). We chose these two pools because they were the largest and deepest of the six pools found on the preliminary site visit, therefore they were more likely to hold water throughout the one-month study period regardless of additional precipitation. Although the entire site was box-scraped by a previous landowner, all the remaining pools will be preserved for mitigation purposes. Caltrans will use this site to obtain mitigation credits for other projects through vernal pool creation, preservation of existing pools, and conversion of existing swales into pools (Vollmar Consulting 2005). None of the planned pool mitigation work has taken place to date on the site.

Precipitation measurements

We used precipitation data from nearby rain gauge stations listed on the California Data Exchange Center website (http://cdec.water.ca.gov), managed by the California Department of Water Resources. For daily data, we used records from the Friant Dam station (FRT). Located in Fresno County, approximately six miles northeast of our site (Figure 1), it is the closest that records daily precipitation data. We downloaded daily rainfall for the period from 2/17/06 to 3/31/06, which includes the two weeks prior to our first site visit through our last site visit. We also analyzed historical rain trends using data from the Fresno WB AP station (FRO). Located in Fresno County, approximately thirteen miles south of our site (Figure 1), it is the closest gauge with long-term monthly precipitation data. We downloaded monthly rainfall accumulation for the period of record from January 1905 to March 2006; the monthly data between January 1981 and September 1982, as well as the month of March 1983, were missing.

To analyze our daily precipitation data, we calculated the mean, maximum, minimum, and total daily rainfall during the study period (2/17/06 to 3/31/06), and plotted the results. To analyze our historical precipitation data, we calculated the mean, maximum, and minimum during the period of record (January 1905 to March 2006). We then selected the March accumulation for each year and plotted these values. Leaving out the years of 1981 to 1983, for which data were missing, we calculated the mean, maximum, and minimum of the March accumulation for the period of record and compared these values with our study period (March 2006). We also determined the total rainfall accumulation for each water year by summing the monthly values, and plotted water year accumulation. We removed the partial or missing water years of 1981 and 1982, although we included the water year of 1983, which only lacked data for the month of March. We then calculated the mean, maximum, and minimum rainfall of the water years for the period of record and compared our study period with these results.

Pool morphology measurements

Figure 3. We measured the length of the long axis and its perpendicular axis during each site visit (photo: Pool 29, 3/3/06).

On our first site visit (3/3/06), we found the longest axis through trial-and-error measurements. During each site visit, we measured the distance between the edges of each pool along this long axis as well as its approximate perpendicular axis (Figure 3). Because the pool edge was not distinct, we estimated it to be where the ponded water was greater than or equal to one inch (versus saturated soil). We then calculated pool surface area from each site visit using the axis measurements in the area equation for ellipses: Surface Area = pab, where a and b equal half the distance of the two measured axes. We chose this method for calculating area because the pools are more elliptical than circular in shape.

During each site visit, we measured the depth of both pools at even intervals along the long axis using a level rod. In addition, we counted our paces (calibrated along measuring tape) around the pools to estimate the perimeter distance.

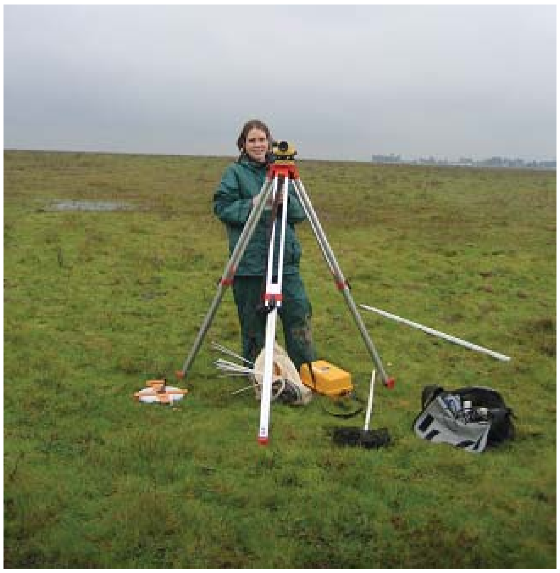


Figure 4. We surveyed the pools during the second site visit using a level and rod (photo: Pool 29, 3/17/06).

During our second site visit (3/17/06), we used standard hydrology survey methods (Dunne and Leopold 1978) to conduct cross section surveys along both axes. Our benchmark for Pool 29 was a rebar stake with flagging that we pounded into the ground; a concrete footing from a nearby telephone tower served as our benchmark for Pool 53. An altimeter provided rough estimations of these benchmark elevations since no USGS benchmarks or other known elevations were in the vicinity. We set up the level along both axes of each pool, measured the distance and angle from the level to the benchmark, and surveyed the pool along both axes (Figure 4), taking note of the substrate and vegetation conditions. We plotted pool morphology as cross section profiles and annotated the plots with vegetation data. We also calculated the slope from the edge of the pool to the lowest point, noting these values on the cross section plots. Finally, we compared the survey results from the two pools to identify differences and similarities.

On the second and third site visits, we made sketch maps of the pools. Once back from the field, we redrew our sketch maps using the measured axes to reduce distortion, scanned the pool outline sketches, and annotated the drawings to represent site conditions.

Water quality measurements

During each site visit, we measured pH, conductivity, dissolved oxygen and temperature with

Figure 5. We used water quality meters to measure temperature, pH, conductivity, and dissolved oxygen during each site visit (photo: Pool 53, 3/3/06).

water quality meters along the long axis (Figure 5). We were short on time during the first site visit, so we only measured water quality at one point along the long axis for each pool; we chose that point near the midpoint (to correspond with the fourth, or middle, temperature sensor). During all of the site visits, we measured pH as (log [H+]) using an Oakton pH Testr 2 waterproof, handheld meter, which we calibrated at pH 4, 7, and 10 in the field prior to operation and checked in pH 7 solution after operation. We measured conductivity (uS), salinity (ppt), and temperature (°C) using a YSI 30 meter, and dissolved oxygen (mg/L and % saturation) using a YSI 55 meter. We placed the probes of the two YSI meters along the bottom of the pool and allowed them to equilibrate for 30 seconds to one minute before we took a reading in each new location. This equilibration time sufficiently minimized mixing from our movement between sites. We held the pH meter several inches below the surface, but not along the bottom of the pond (not physically possible due to design of this meter), and allowed it to equilibrate for the same time period.

Temperature sensor measurements

On our first site visit (3/3/06), we placed eight automatic temperature sensors (deployable for up to four months) at even intervals on the pool bottom along the long axis. The LA 222 graduate student instructor, from whom the I-Button temperature sensors were borrowed, calibrated the sensors by submersion in an ice bath during the week before they were deployed. All were found to be performing to within ±0.5 °C accuracy in agreement with specifications. Using a laptop in the field, we preprogrammed the I-Button temperature sensors to conduct temperature recordings every 15 minutes with a resolution of 0.0625 °C, and to automatically log data with no rollover. We placed the temperature sensors inside plastic water balloons to protect them from water damage (calibration was performed with balloons; Tompkins 2006), then inside small burlap sacks attached to survey flags with plastic cinch ties; these flags

Figure 6. We secured the temperature sensors to survey flags placed at even intervals along the long axis of each pool during the first site visit (photo: Pool 53, 3/3/06).

were then stuck into the mud substrate to secure the temperature sensors along the pool bottom (Figure 6). On our third site visit (3/31/06), we attempted to recover the I-Button temperature sensors. However, the cows had eaten the flagging and the pools were deeper than previous visits, so we only managed to recover six out of sixteen sensors; all from Pool 53.

Data from the six recovered temperature sensors were downloaded using the One Wire Viewer software as a text file, which was then imported into Excel. We performed statistical analyses using JMP-In v5.1 with standard least squared regression and ANOVA to determine: 1) if there was a spatial temperature gradient; 2) how temperature patterns related to rainfall patterns; and 3) how these factors related to the other parameters and if there were are any significant correlations between them.

Invertebrate surveys

On the preliminary reconnaissance visit (2/10/06), and then on the second and third site visits, we conducted an invertebrate presence-absence survey in the two study pools. We swept a standard nine inch (in) by seven in aquarium net (one millimeter mesh size), mounted on the end of a four foot (ft) long pvc pipe, through the water column along the long axis. We then examined the contents of the dip net for invertebrate and amphibian species, which we identified in the field at the known taxonomic level (usually order, but species-level for branchiopods). No samples were collected and all individuals were returned to each pool unharmed.

Results

Precipitation

During the study period from 2/17/06 to 3/31/06, rain gauge data indicate that our site received 4.76 in of rain, and the amount of rainfall increased throughout the month (Figure 7). For the entire January 1905 to March 2006 period of record, the average monthly rainfall was 0.86 in and the maximum monthly rainfall was 8.56 in. In considering only the month of March during this period of record, the average monthly rainfall was 1.76 in and the maximum monthly rainfall was 7.24 in (Figure 8). During our study period in March 2006, the site received 4.73 in of precipitation (FRO historical data), which is 269% of the average March monthly rainfall; only four other months of March exceeded the 2006 accumulation during the 101-year period of record. During the water years from 1906 to 2005, the average rainfall accumulation was 10.17 in, the maximum water year accumulation was 23.06 in (in 1969), and the minimum water year accumulation was 4.44 in (in 1934) (Figure 9). The partial 2006 water year data (through 3/31/06) indicate that the site received 10.89 in of rain during this water year thus far, which is 107% of the average water year accumulation.

Pool morphology

Both pools are oval in shape, with the long axis generally in the north-south direction. Pool 29 is a large, shallow pool with gradual slopes along its axes from the edge of the pool to its lowest point ranging from 1.4% to 2.0%. The substrate is mildly undulating and consists of mud and the plant Eryngium sp. towards the middle of the pool, while grass dominates the edges (Figure 10). Pool 53 is a smaller, deeper pool with steeper slopes ranging from 1.9% to 4.5%. The substrate undulates more significantly in this pool, and it also consists of mud and Eryngium towards its center. Eryngium has also established at and near the pool edges, along with grass (Figure 11).

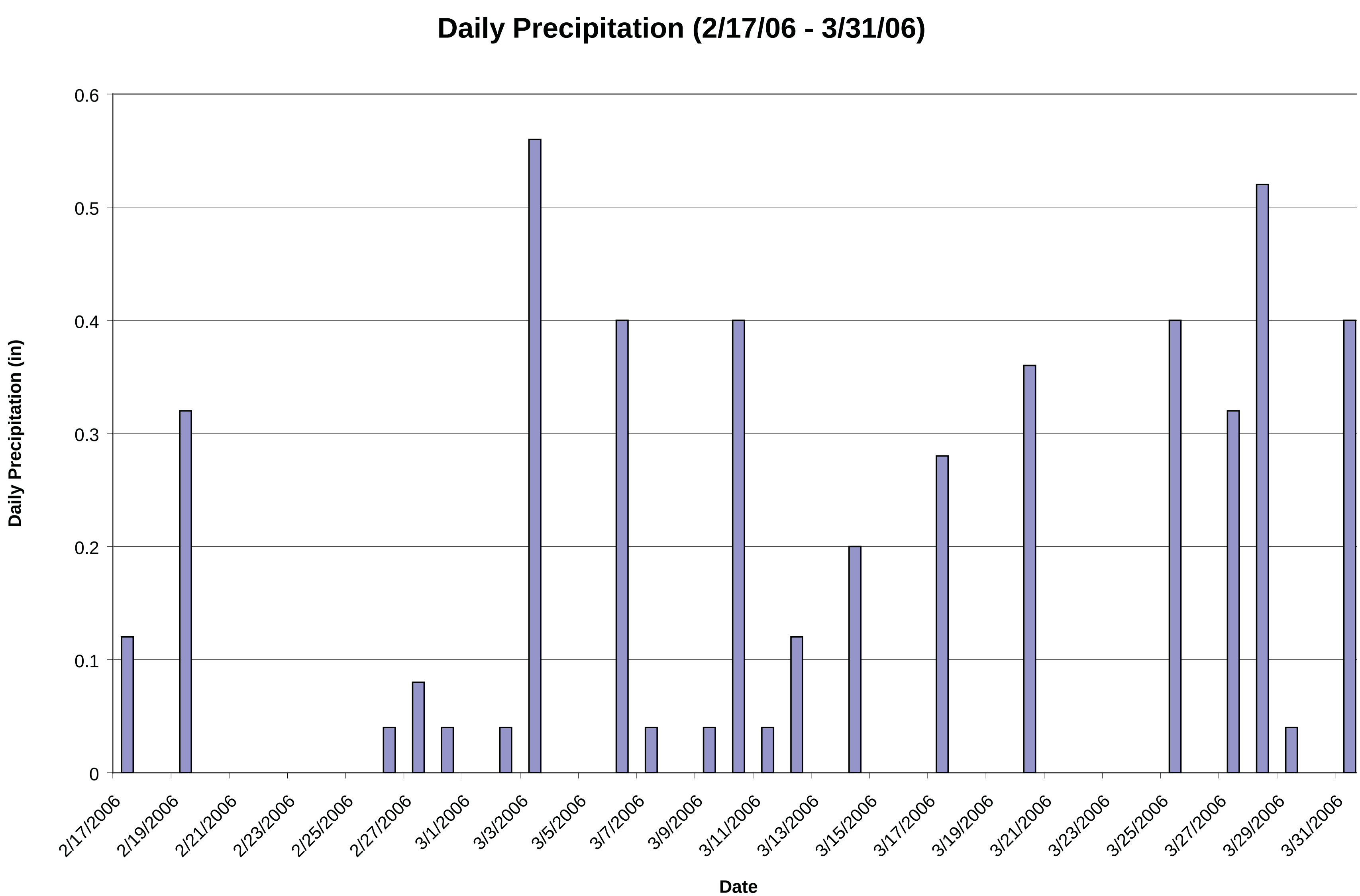


Figure 7. Daily precipitation data (in inches) during the period from 2/17/06 to 3/31/06 (our study period plus two weeks prior) at the Friant Dam Station is shown. The average daily rainfall was 0.11 in and the maximum daily rainfall was 0.56 in (on 3/3/06). The total rainfall during this period was 4.76 in.

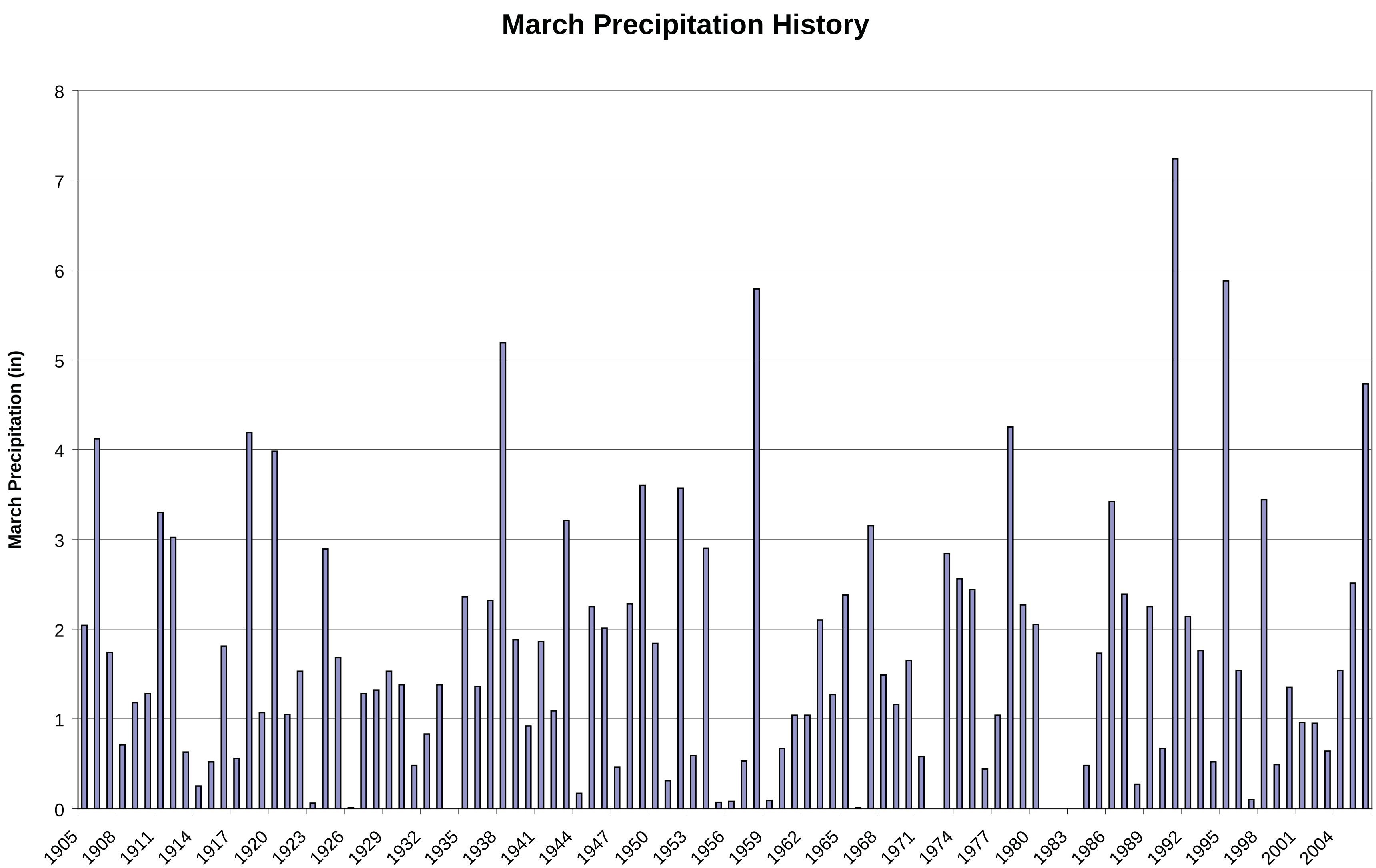


Figure 8. Monthly precipitation accumulation (in inches) during only the month of March from 1905 to 2006 at the Fresno WB AP Station is shown (station records are missing data from 1981 to 1983). March 2006 was the fifth rainiest March during this period of record, 269% of the average March accumulation.

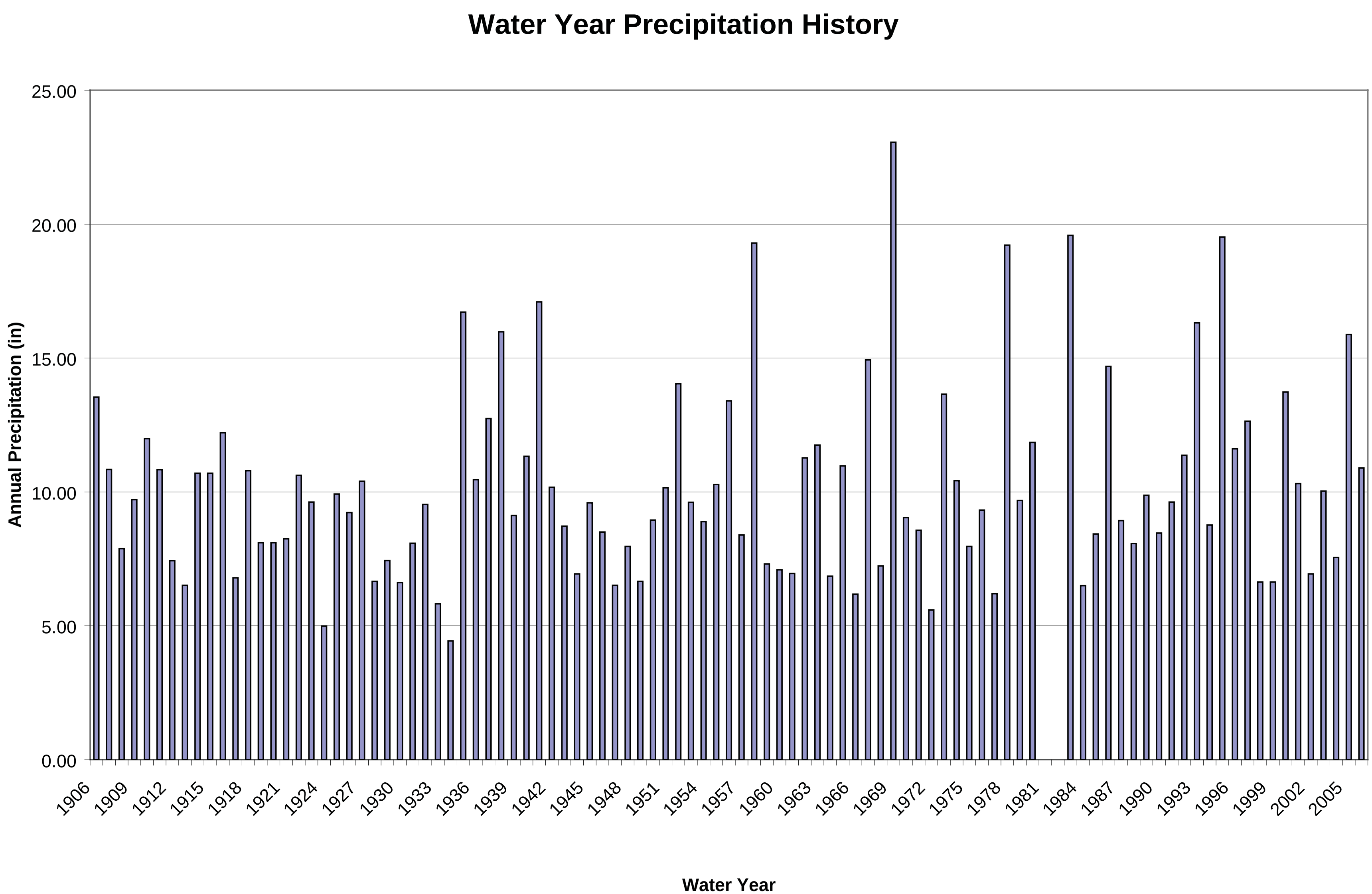
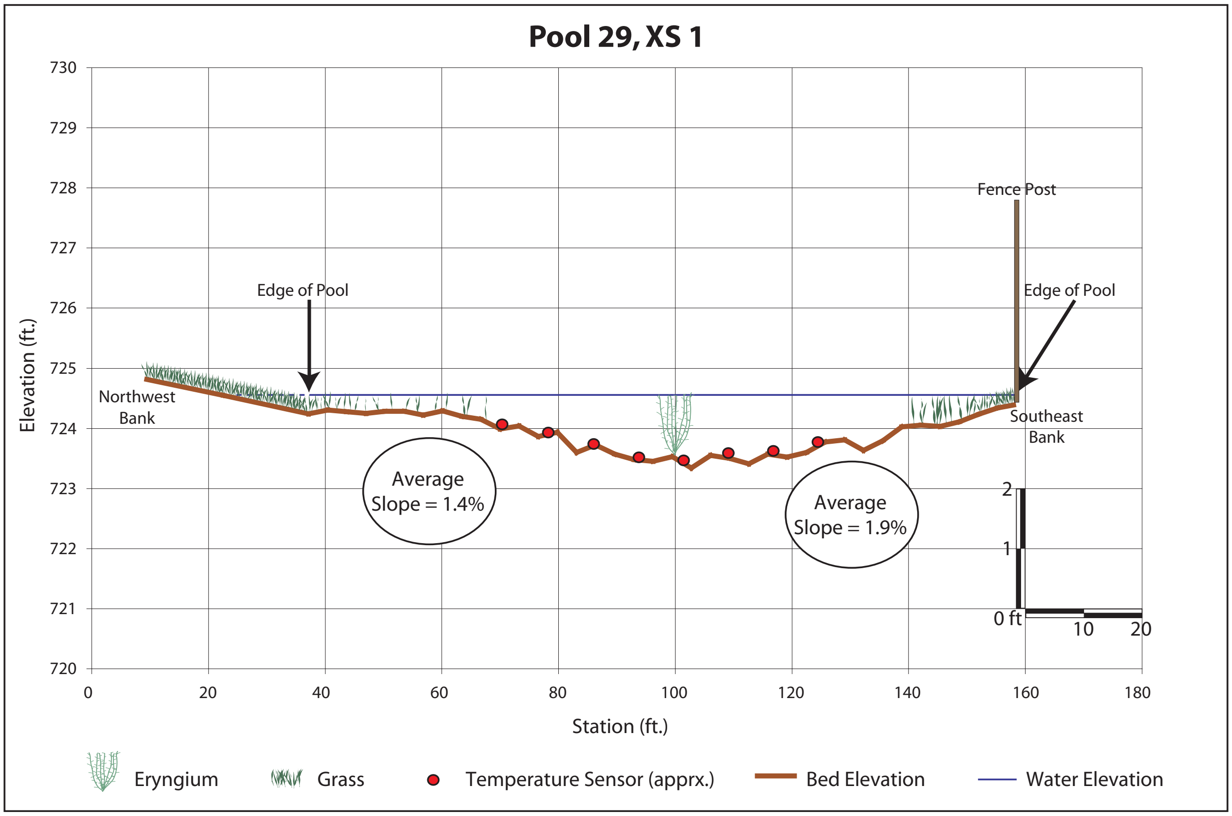


Figure 9. Water year precipitation accumulation (in inches) from 1906 to 2006 at the Fresno WB AP Station is shown (station records are missing data from 1981 to 1982 and only includes partial data from water years 1983 and 2006). The average water year rainfall accumulation was 10.17 in., the maximum was 23.06 in (in 1969), and the minimum was 4.44 in (in 1934).



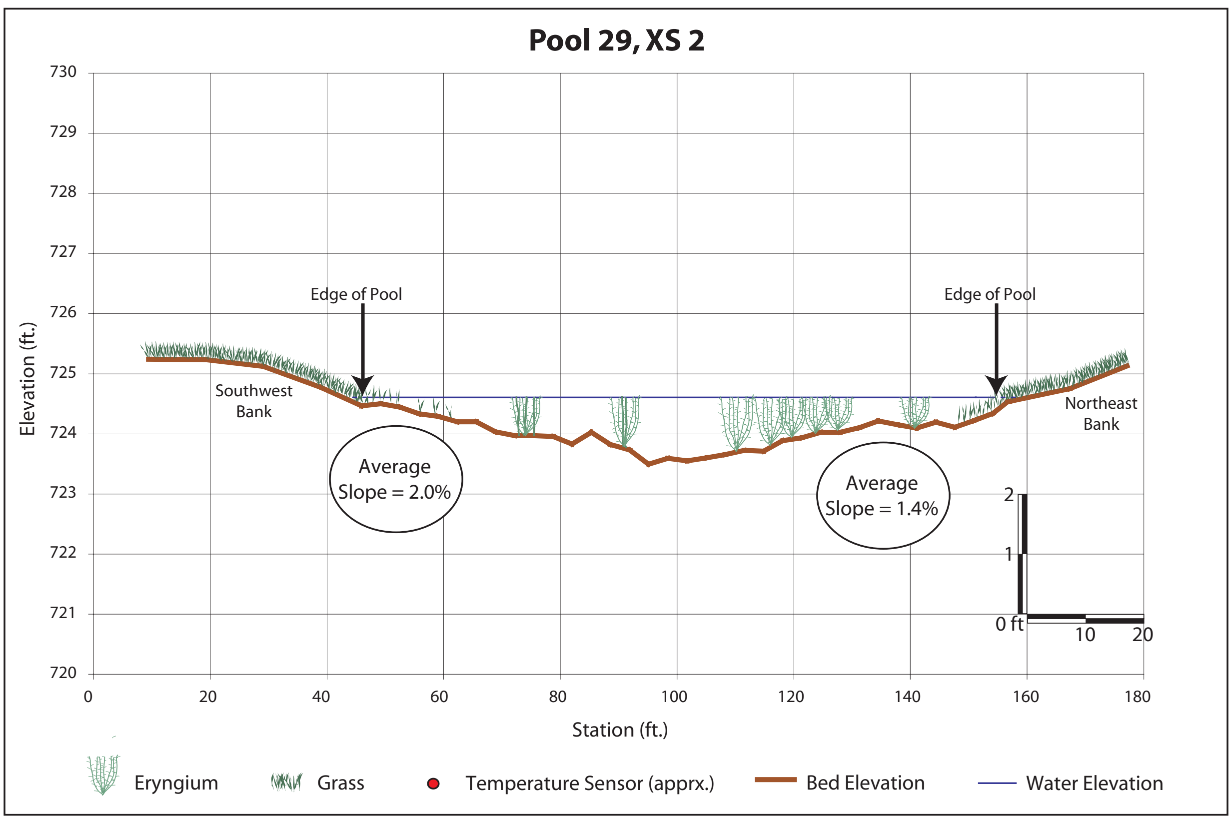
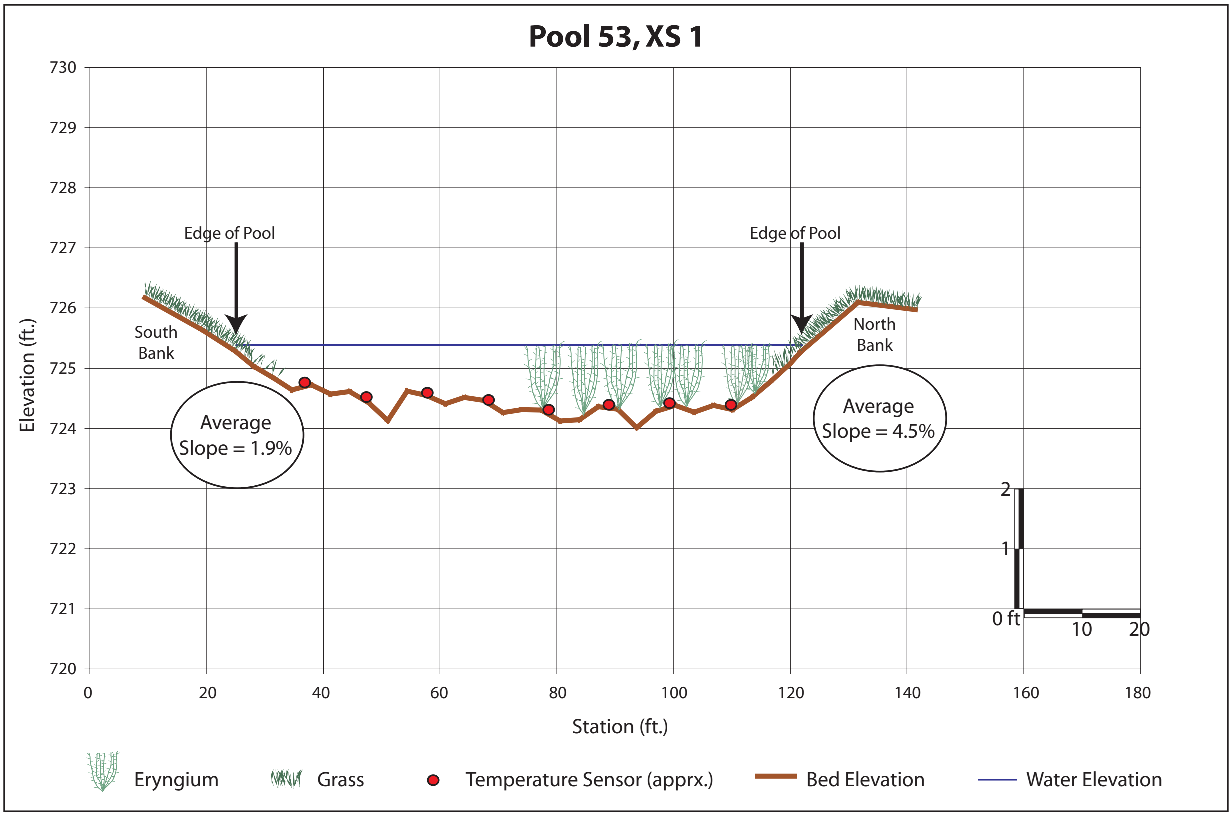


Figure 10. Pool 29 is a shallow, large pool with gradual slopes. Cross sections of the long axis (XS1) and the perpendicular axis (XS2) are displayed with an approximate 10X vertical exaggeration.



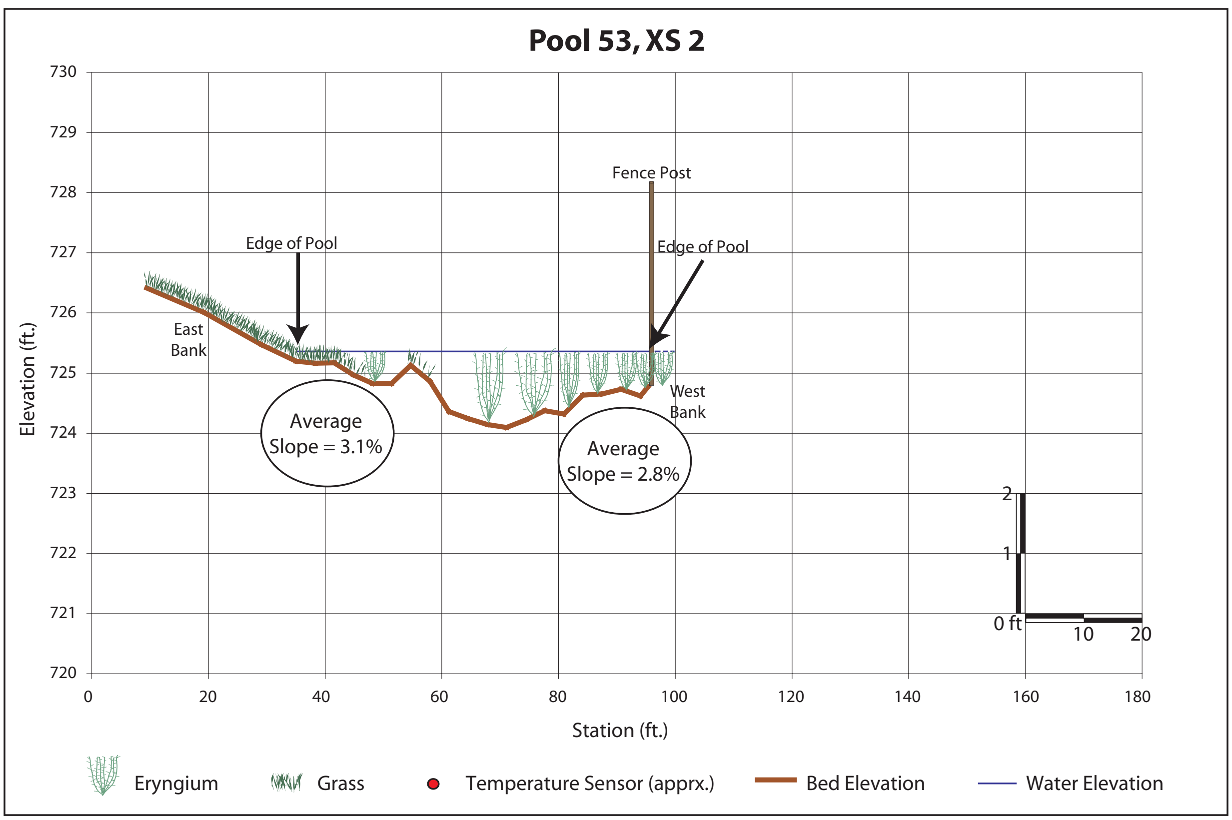


Figure 11. Pool 53 is a smaller, deeper pool with steeper slopes. Cross sections of the long axis (XS1) and the perpendicular axis (XS2) are displayed with an approximate 10X vertical exaggeration.

Trends over one month

In general, the length of each axis, average depth, maximum depth, pool area, and pool circumference increased with each site visit (Table 1, Figures 12 – 15). However, between the second and third site visits, Pool 53 decreased in length along each axis (Figure 13), which resulted in a decreased pool surface area, while the maximum pool depth also decreased. Pool 29 significantly increased in area after the first site visit due to precipitation, exceeding Pool 53's area for the remainder of the study period. Meanwhile, the average depth of Pool 53 significantly increased after the first site visit, exceeding Pool 29's average depth during the second site visit and equaling it during the third site visit.

	3/3/2006				**3/17/2006**				**3/31/2006**			
Pool #	29		53		29		53		29		53	
Axis (Prp= Perpendicular)	Long	Prp	Long	Prp	Long	Prp	Long	Prp	Long	Prp	Long	Prp
Average daily temperature (degrees F)	45				48				53			
Cumulative rainfall (2 weeks prior) (in)	0.64				1.8				1.92			
Axis Length (ft)	60	53	83	41	127	117	96	61	142	122	92	53
Axis Average Depth (ft)	0.55	-	0.5	-	0.67	0.60	0.90	0.72	0.84	-	0.84	-
Pool Average Depth (ft)	0.55		0.50		0.64		0.83		0.84		0.84	
Axis Max Depth (ft)	0.69	-	0.9	-	1.24	1.12	1.41	1.33	1.42	-	1.19	-
Pool Max Depth (ft)	0.69		0.9		1.24		1.41		1.42		1.19	
Pool Area (ft2)	2498		2673		11670		4599		13606		3830	
Pool Perimeter (ft)	190		-		500		290		610		340	

Table 1. The average daily temperature, rainfall accumulation, axis length and depth, and pool area and perimeter increased during the study period, although pool 53 decreased in area and maximum depth between 3/17/06 and 3/31/06. Average daily temperature during each site visit and rainfall accumulation for the two weeks prior to each site visit were collected from the Friant Dam Station, located approximately six miles from our site. The axis length and depth values display our field measurements from each site visit. The area values are based on the axis length field measurements (using the area equation for ellipses). The perimeter values are based on our field approximations from pacing the perimeter.

Figure 12a

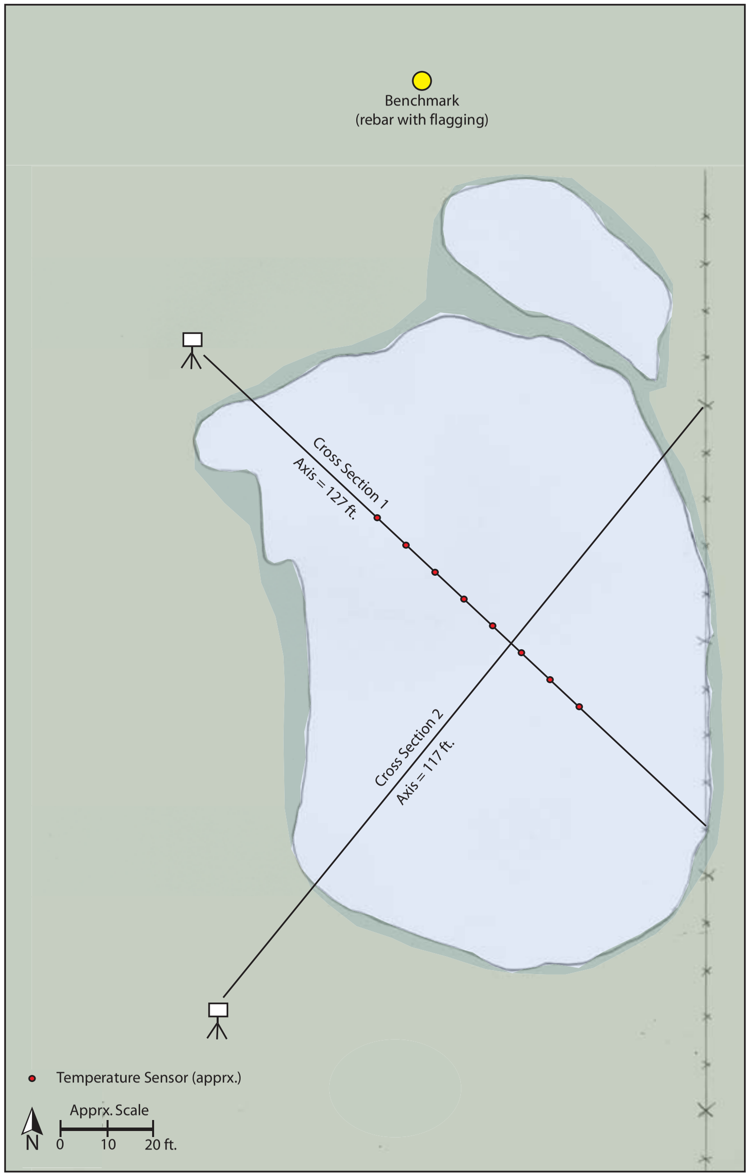


Figure 12b

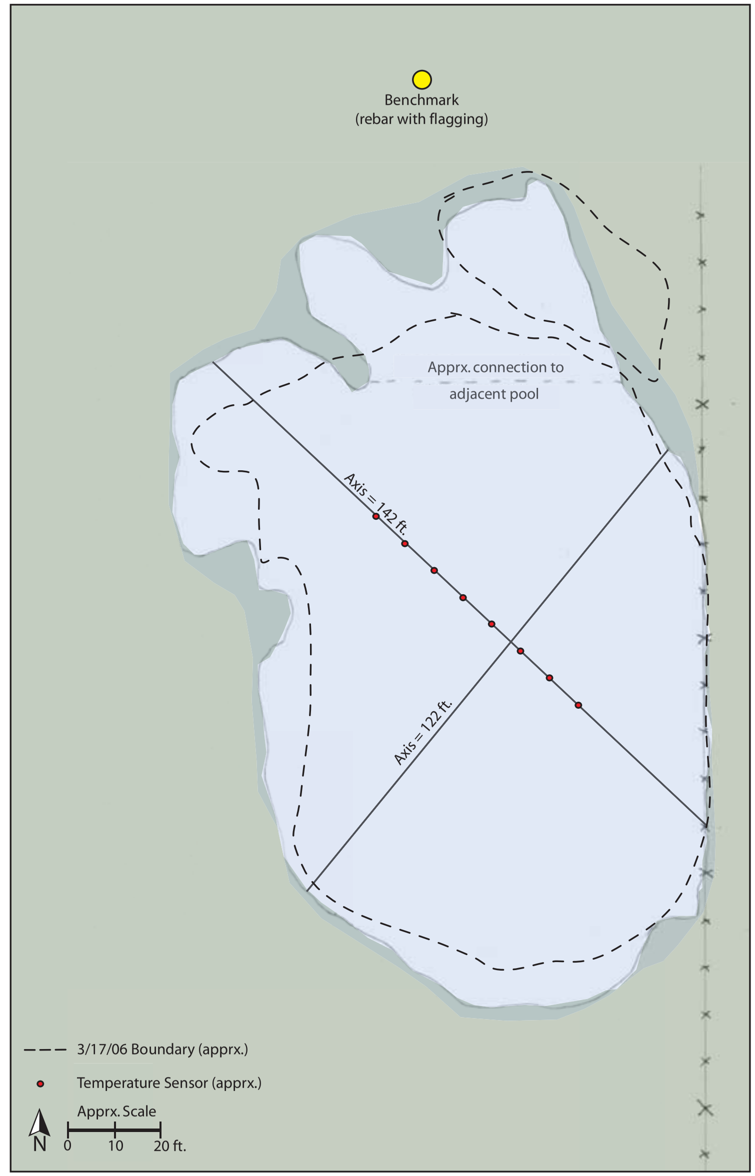


Figure 12. Pool 29 increased in area over the study period. a) On 3/17/06, the pool area was approximately 11,670 ft2; and b) on 3/31/06 the pool area had increased to approximately 13,606 ft2. The dashed line in figure 12b indicates the 3/17/06 pool boundary.

Figure 13a

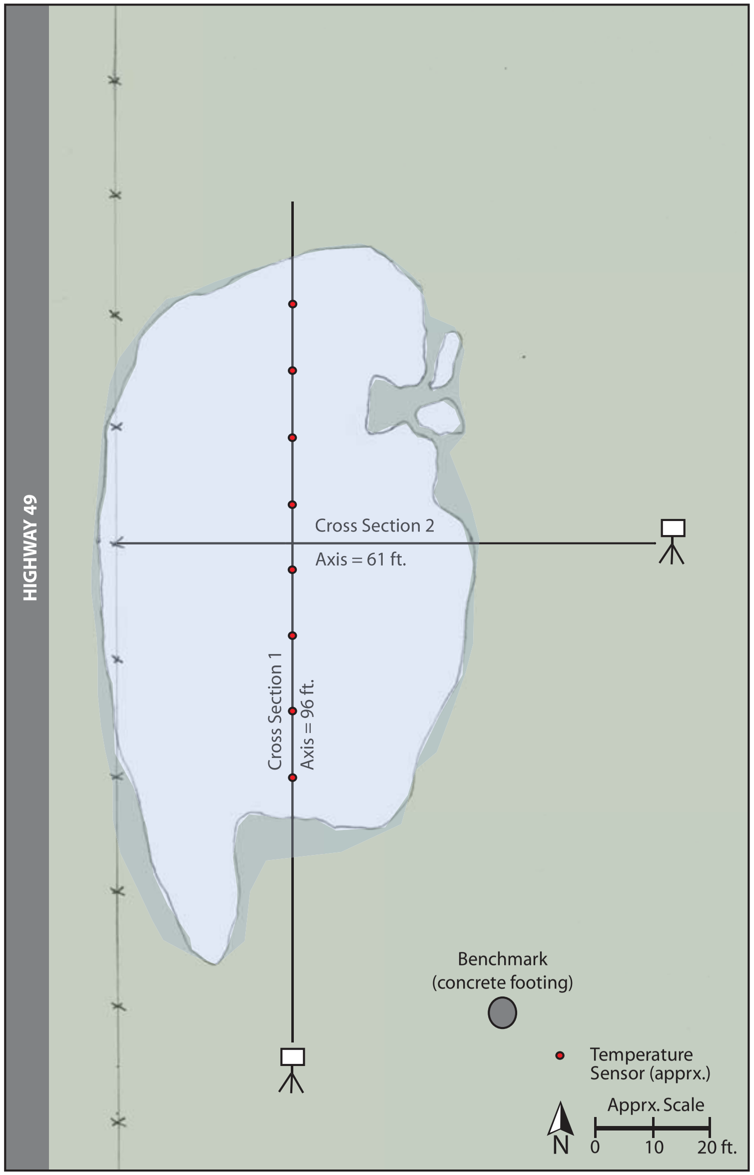


Figure 13b

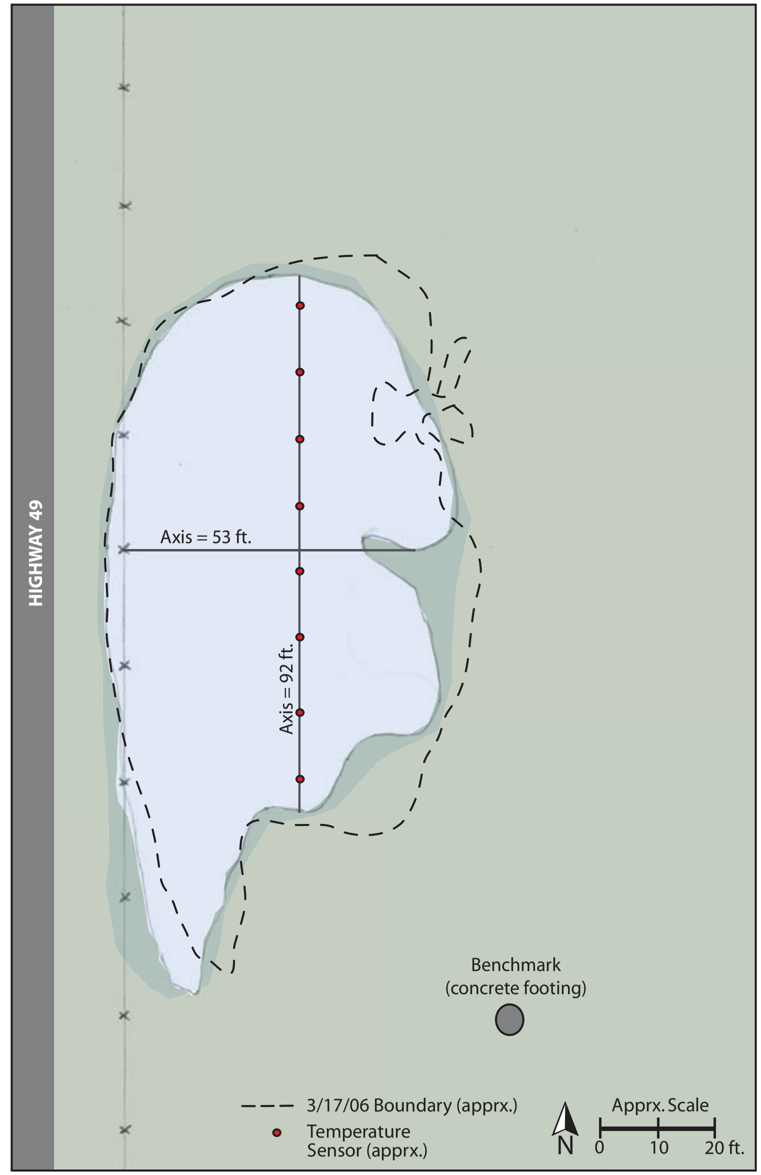


Figure 13. Pool 53 decreased in area over the study period. a) On 3/17/06, the pool area was approximately 4,599 ft2; and b) on 3/31/06 the pool area had decreased to approximately 3,830 ft2. The dashed line in figure 13b indicates the 3/17/06 pool boundary.

Figure 14a

Figure 14b

Figure 14c

Figure 14. Pool 29 increased in both area and depth over the study period. a) On 3/3/06, Pool 29's area was 2,498 ft2 and the maximum depth was 0.69 ft; b) on 3/17/06, its area was 11,670 ft2 and the maximum depth was 1.24 ft; and c) on 3/31/06, its area was 13,606 ft2 and the maximum depth was 1.42 ft.

Figure 15a

Figure 15b

Figure 15c

Figure 15. Pool 53 decreased in area over the study period. a) On 3/3/06, Pool 53's area was 2,673 ft2 and the maximum depth was 0.90 ft; b) on 3/17/06, its area was 4,599 ft2 and the maximum depth was 1.41 ft; and c) on 3/31/06, its area was 3,830 ft2 and the maximum depth was 1.19 ft.

Water temperature increased in both pools over March, supported by both sets of temperature data. The temperature sensor data showed a clear increasing trend over the month of March (Figure 16). The average temperature (calculated from data collected by YSI water quality meter) went from 9.5 to 14.5 °C for Pool 29 and from 11.0 to 16.8 °C for Pool 53. Average pH decreased over March for both pools: pH for Pool 29 went from 8.1 to 7.3 and pH for Pool 53 went from 8.0 to 7.2. Average dissolved oxygen (DO) had different patterns for the two pools over March: for Pool 29 DO increased over the month but peaked at the second visit, while for Pool 53 DO remained fairly constant over the month. Average conductivity did not show a clear trend: for Pool 29 conductivity decreased then increased, with an overall decrease, while for Pool 53 conductivity also decreased then increased, but with an overall increase. Table 2 and Figure 17 display these water quality trends over our study period.

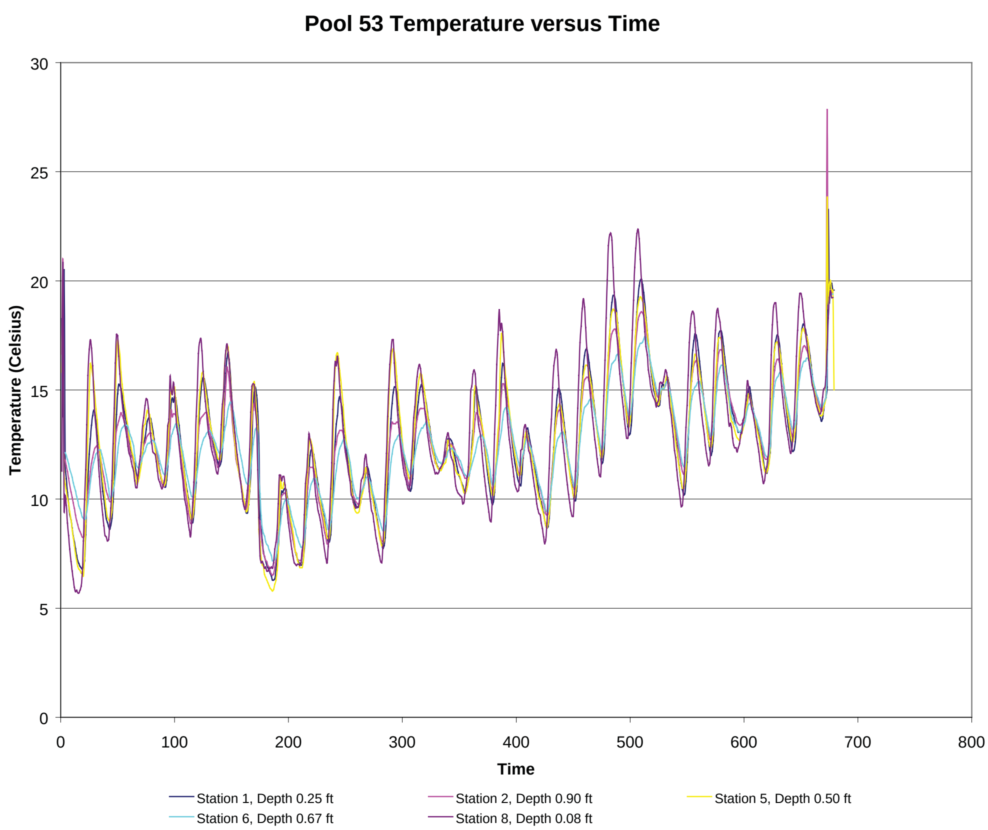


Figure 16. Pool temperature increased over time and fluctuated diurnally. Temperature (°C) was measured at the bottom of Pool 53 using I-Button data logging temperature sensors, deployed from March 3 – 31, 2006 (672 hours total). Station number refers to individual sensors placed along the long axis of the pool. Depth indicates the water level above each sensor station on 3/3/2006, the date the sensors were deployed.

		Average					Minimum					Maximum				
Pool	Date	Temperature (°C)	pH	DO (mg/L)	Conductivity (uS)	I-Button Temperature (2 wks prior, °C)	Temperature (°C)	pH	DO	Conductivity	I-Button Temperature (2 wks prior, °C)	Temperature (°C)	pH	DO	Conductivity	I-Button Temperature (2 wks prior, °C)
29	3/3/2006	9.5	8.1	3.94	202.80	NA					NA					NA
	± Std Dev*	*	*	*	*											
29	3/17/2006	12.1	8.2	7.41	90.20	NA	11.7	6.9	0.35	76.90	NA	13.3	8.7	10.81	110.80	NA
	± Std Dev, n = 38	0.43	0.62	2.328	6.616											
29	3/31/2006	14.5	7.3	5.69	129.28	NA	14.4	6.6	2.93	121.69	NA	14.9	7.4	7.20	185.59	NA
	± Std Dev, n = 43	0.13	0.15	0.945	11.019											
53	3/3/2006	11.0	8.0	4.58	131.50	NA					NA					NA
	± Std Dev*	*	*	*	*											
53	3/17/2006	13.1	7.4	4.82	118.60	11.40	12.6	7.3	0.38	108.60	5.70	13.9	7.7	10.87	136.00	20.90
	± Std Dev, n = 29-31	0.30	0.11	2.095	8.250											
53	3/31/2006	16.8	7.2	4.76	149.75	14.03	16.0	7.2	2.14	144.60	7.96	17.7	7.2	6.75	174.80	29.27
	± Std Dev, n = 27	0.35	0.00	1.206	6.640											

* water qlty msmt from 1 data point therefore no std dev, min, max, or med available

Table 2. Trends in water quality were observed over the one-month study period. Trends were calculated as average, minimum, and maximum for each parameter measured in each pool at each site visit. YSI water quality meter temperature was recorded at each site visit for both pools, while I-Button sensor temperature was recorded continuously from 3/3 – 3/31/2006 for Pool 53.

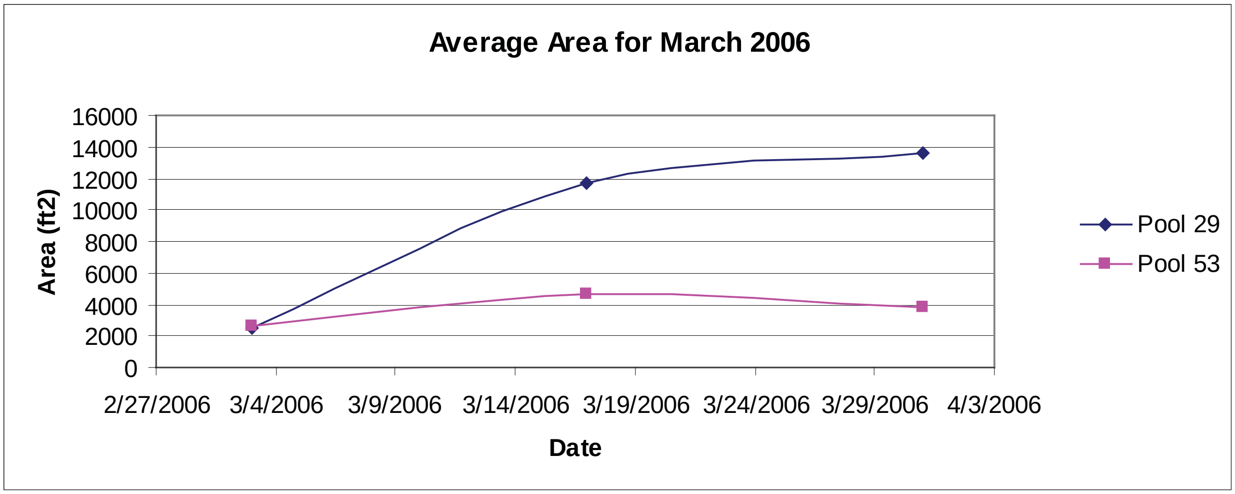


Figure 17a

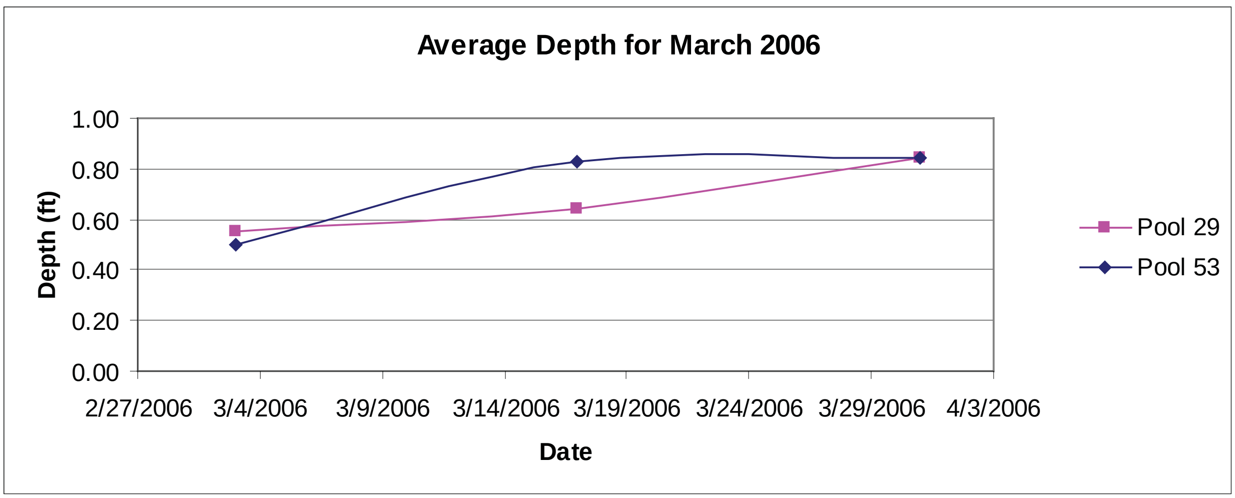


Figure 17b

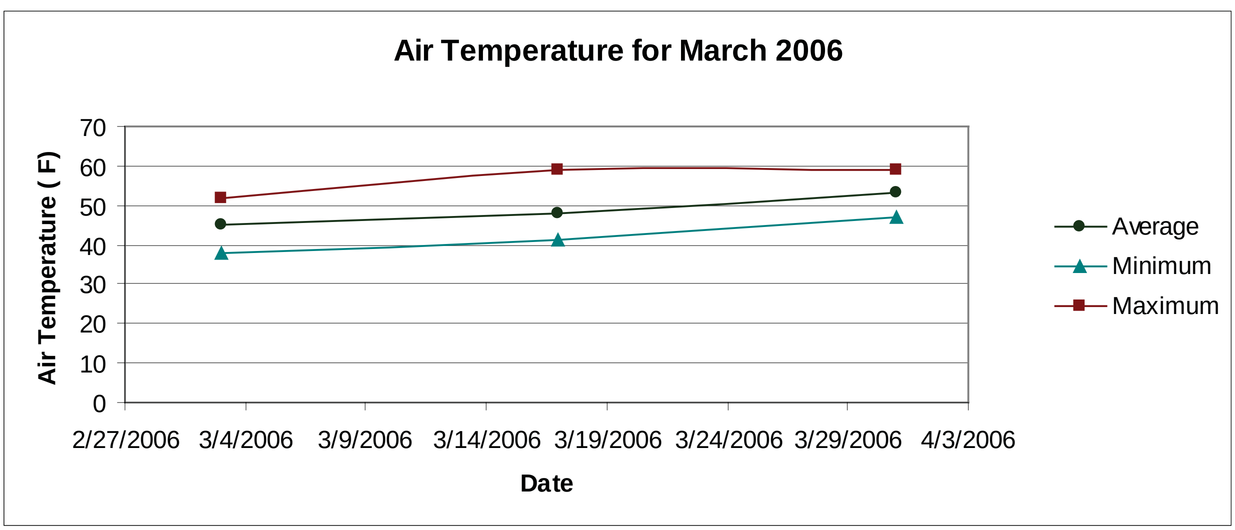


Figure 17c

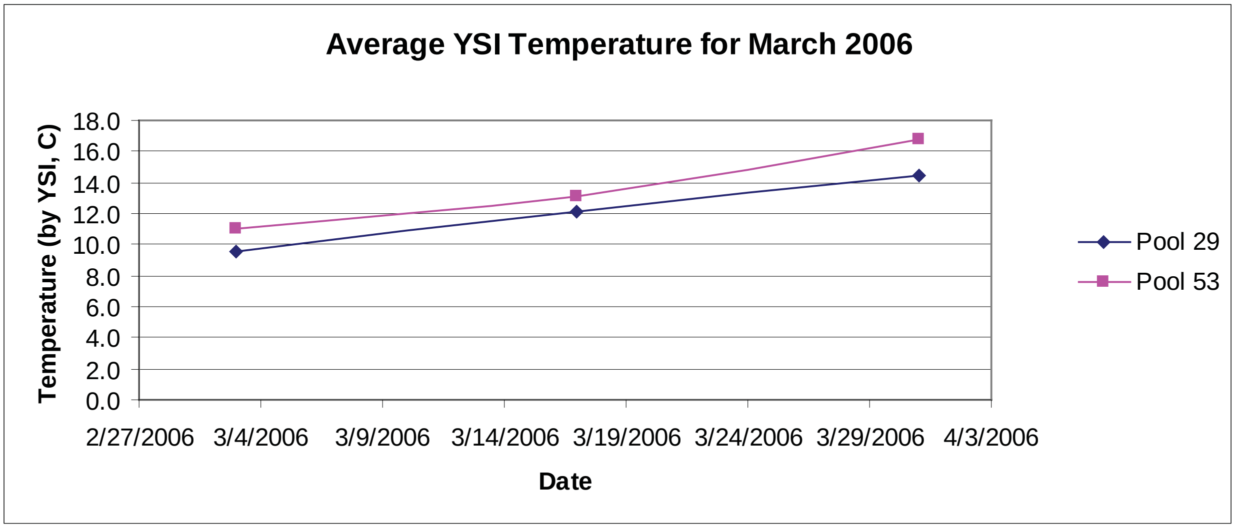


Figure 17d

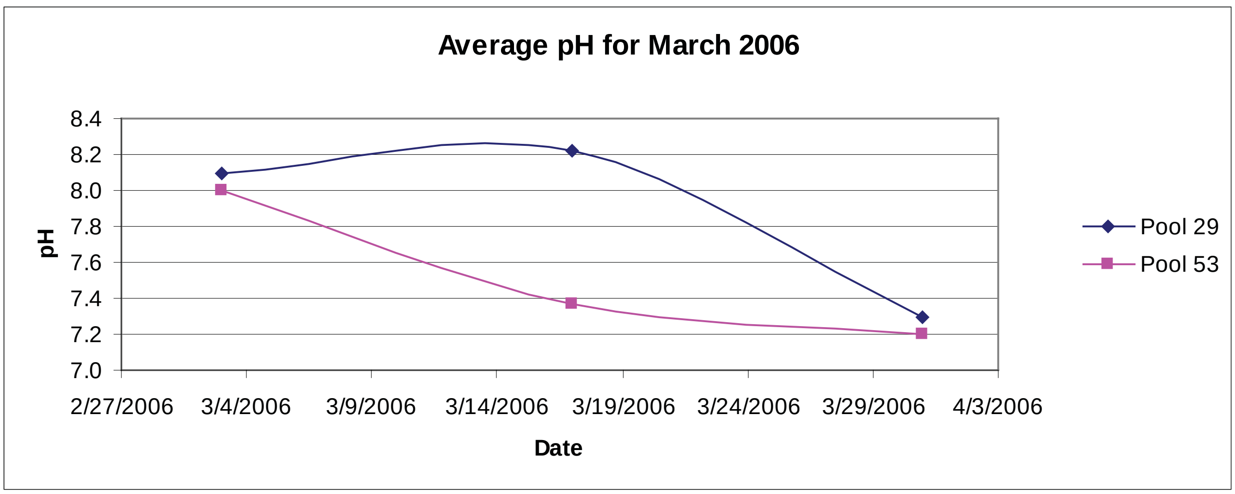


Figure 17e

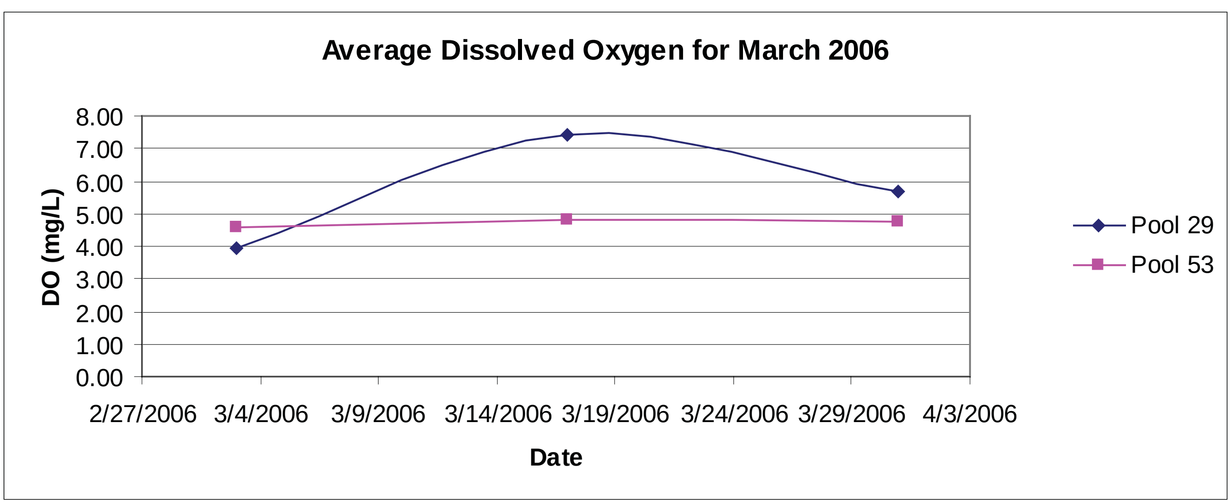


Figure 17f

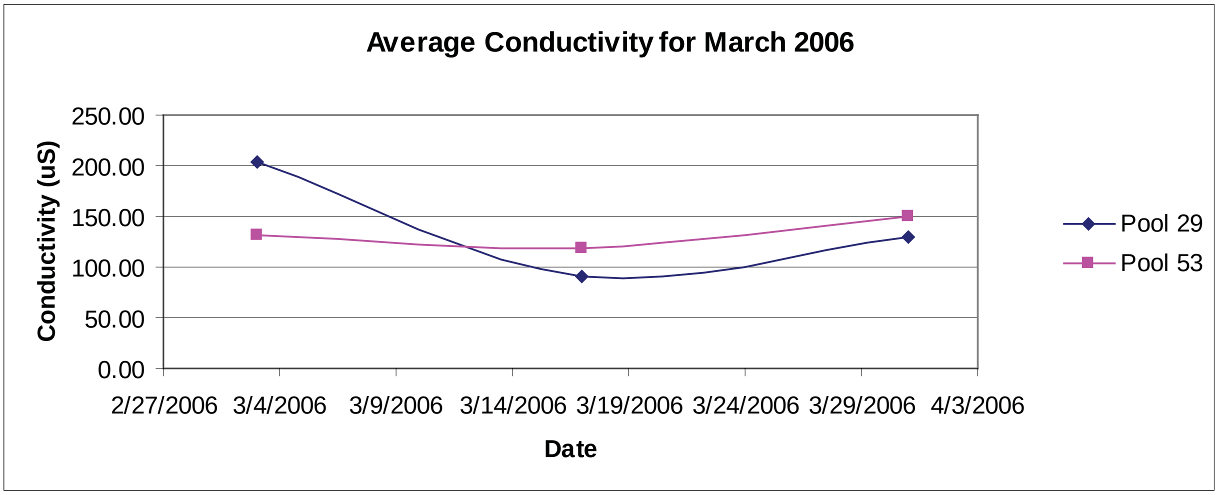


Figure 17g

Figure 17. Trends in pool morphology and water quality were observed over the one-month study period. Each trend includes three data points, each an average of the measurements for the parameter at each site visit, conducted on 3/3, 3/17, and 3/31/2006. a) Average area (ft2) increased for Pool 29 and decreased for Pool 53; b) average depth (ft) increased for both pools; c) average, minimum, and maximum air temperature (°F) increased; d) average pool temperature (measured by YSI water quality meter, °C) increased for both pools; e) average pH decreased for both pools; f) average dissolved oxygen (mg/L) increased then decreased for Pool 29, but stayed fairly constant for Pool 53; and g) average conductivity (uS) decreased then increased for Pool 29, but increased only slightly for Pool 53.

To examine whether pool area or depth had a significant relationship over time with precipitation or air temperature, we performed linear regressions (Table 3, Appendix A). For performing these regressions we used cumulative rainfall for the two weeks prior to each site visit: 0.64 in for 3/3/2006, 1.8 in for 3/17/2006, and 1.92 in for 3/31/2006. We used average daily air temperature, which increased over the study period (Table 2 and Figure 17c). The relationships between pool area versus cumulative precipitation were significant for Pool 29 but not for Pool 53, whereas the relationships between average pool depth versus cumulative precipitation were significant for Pool 53 but not for Pool 29. The relationships between average pool temperature and average air temperature were highly significant for Pool 53 (from both sets of temperature data) but were not significant for Pool 29 (YSI temperature data only).

Y	X	R2	p
P29 Area	Cumulative Precipitation (2 weeks prior)	0.994	0.050
P53 Area	Cumulative Precipitation (2 weeks prior)	0.776	NS
P29 Average Depth	Cumulative Precipitation (2 weeks prior)	0.630	NS
P53 Average Depth	Cumulative Precipitation (2 weeks prior)	0.997	0.038
P29 Average Pool (YSI) Temperature	Average Air Temperature	0.973	NS
P53 Average Pool (YSI) Temperature	Average Air Temperature	1.000	0.009
P53 Average Pool (IB) Temperature	Average Air Temperature	0.741	<0.0001

Table 3. Regressions between pool area, depth, and temperature versus rainfall and air temperature yielded mixed results. Pool area versus cumulative precipitation was significant for Pool 29 only. Pool depth versus cumulative precipitation was significant for Pool 53 only. Average pool temperature versus average air temperature was significant for Pool 53 by both discrete and continuous temperature measurement methods (YSI and I-Button, respectively). All regression fits were linear, where NS = non-significant.

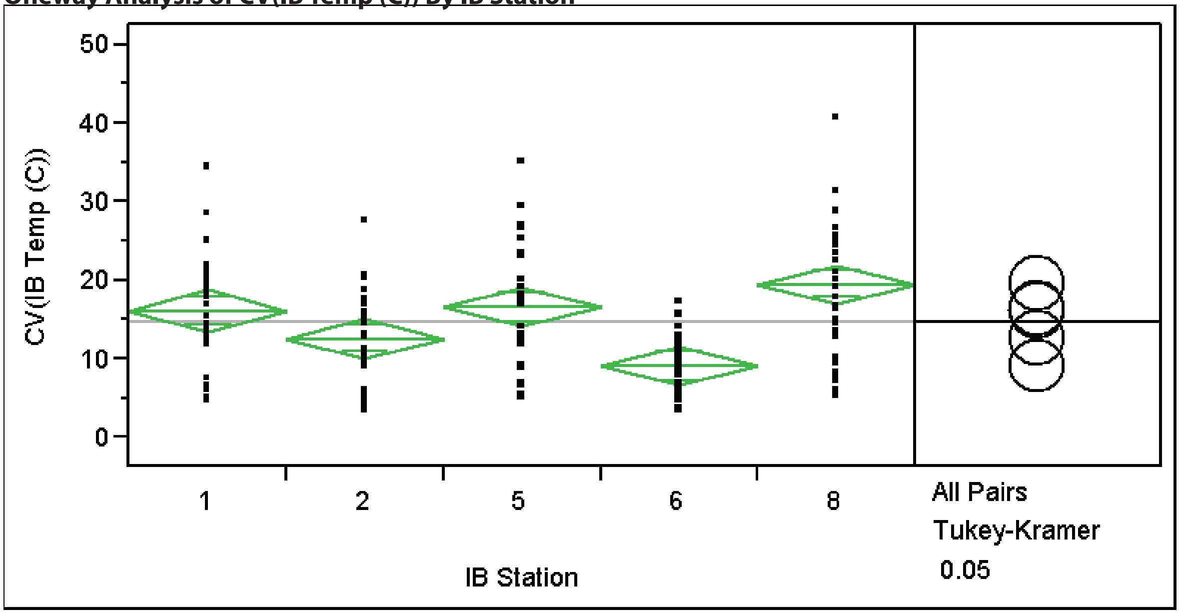
Spatial temperature distribution

To determine if temperature profiles at each station (measured by I-Button temperature sensors) were significantly different, the coefficients of variability (CVs) were calculated as a measure of fluctuation in temperature and analyses of variance (ANOVAs) were performed on the CVs at each station. We chose CV as the measure of fluctuation in temperature because it expresses sample variability relative to the mean of the sample (Zar 1999). The distributions of CVs were homoscedastic, meeting the conditions for performing ANOVA. Two CVs were calculated for: a) temperature versus station at each date, and b) temperature versus station at time of day (i.e., with one-month trend removed). ANOVAs for both CVs were highly significant with $p<0.0001$ (Figure 18; Appendix B), therefore there are significant differences in temperature among stations. This result was further supported by performing the Tukey-Kramer test to determine which temperature stations are significantly different: using both CVs, station 6 showed the lowest temperature fluctuation while station 8 showed the highest (Figure 18; Appendix B). Without the seasonal trend removed (CV with date), station 8 was significantly different from 6 and 2; station 6 was significantly different from 8, 5, and 1; and station 2 was significantly different from station 8 (Figure 18a). With the one-month trend removed (CV with hour), station 6 was more different from all the other stations (Figure 18b).

To further test these findings of a spatial temperature distribution from sensor data, we performed a regression using temperature data collected by YSI water quality meter versus position. Position was defined as the distance from the edge of the pool along the long axis. From these regressions, we again found evidence of a spatial distribution: for both pools the relationship between temperature and position was strong and highly significant on both 3/17 and 3/31 (Figure 19; Table 4). To test if these relationships between temperature and position could be explained equally well by depth, we performed the same regressions between the two sets of temperature data and depth. Depth was defined as the water level above each sensor station during each site visit. Using the CV of temperature sensor data, we found that the relationship with depth was weak but significant (Figure 20; Appendix B). However, from a regression of temperature data measured by water quality meter versus depth, we found the relationships were weaker than those of temperature and position with much lower R2 (and not all p values were significant) (Figure 21; Table 4).

To generate CV used IB Temp vs IB Station and IB Date
Oneway Analysis of CV(IB Temp (C)) By IB Station

Figure 18a



To generate CV used IB Temp vs IB Station and IB Hour
Oneway Analysis of CV(IB Temp (C)) By IB Station

Figure 18b

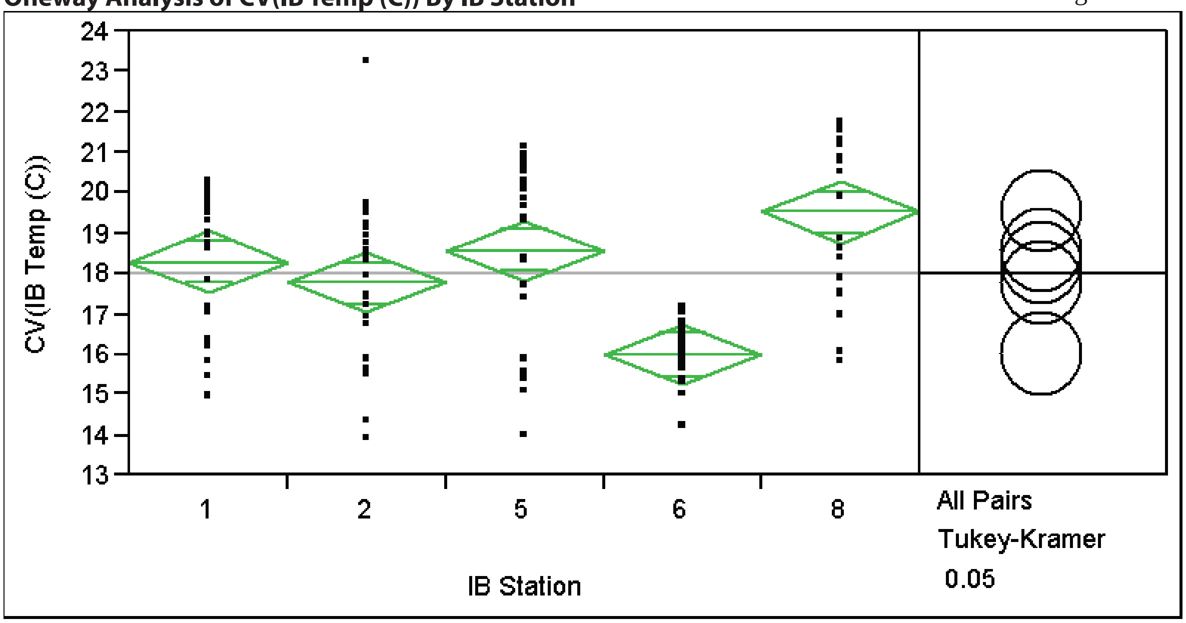


Figure 18. A significant spatial distribution in temperature (measured using I-Button sensors, see Figure 16) was found from the one-way ANOVA of the CV of temperature versus station (the CV captures the fluctuation in each temperature sensor station). The Tukey-Kramer HSD tests show where significant differences among the sensors were located (i.e., how the distribution looks). a) ANOVA with daily trends removed (by calculating CV of temperature versus station and date) shows highly significant spatial temperature distribution ($p < 0.0001$, df = 144). Also in 18a, Tukey HSD shows that stations 8 and 1 group together (i.e., margins are the same and overlap with intermediate station 5); stations 5 and 2 group together (i.e., intermediate regions are the same and overlap with margin station 1); and station 6 is alone but has some overlap with intermediate station 2 (i.e., middle of pool is different from most margin or intermediate stations). b) ANOVA with one-month trends removed (by calculating CV of temperature versus station and hour) shows highly significant temperature distribution ($p < 0.0001$, df = 119). Also in 18b, Tukey HSD showed same pattern as 18a, but station 6 is more different and has no overlap with any other stations (i.e., middle of pool is different from all margin and intermediate stations).

Figure 19a

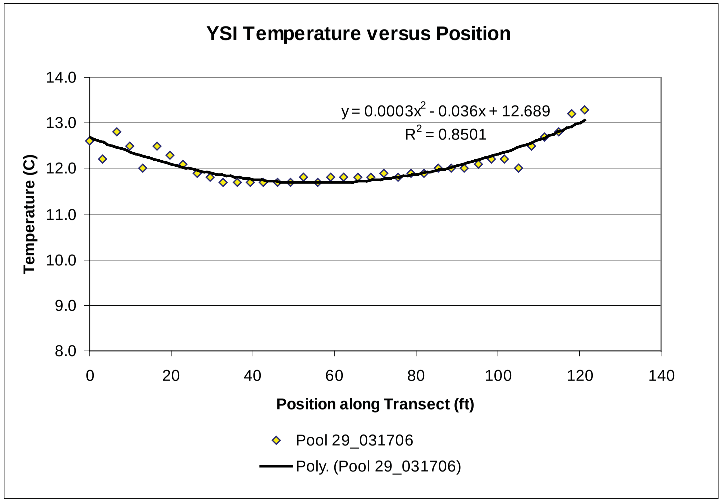


Figure 19c

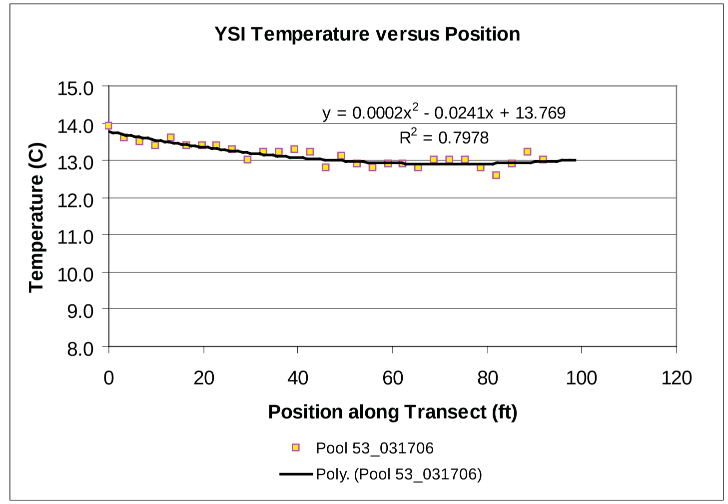


Figure 19b

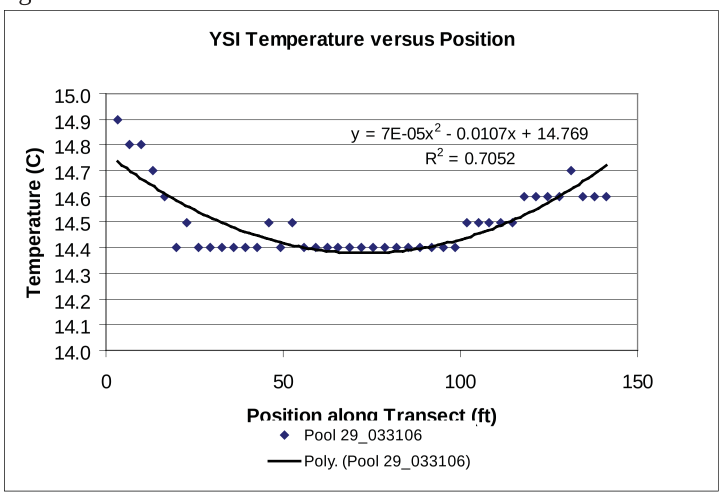


Figure 19d

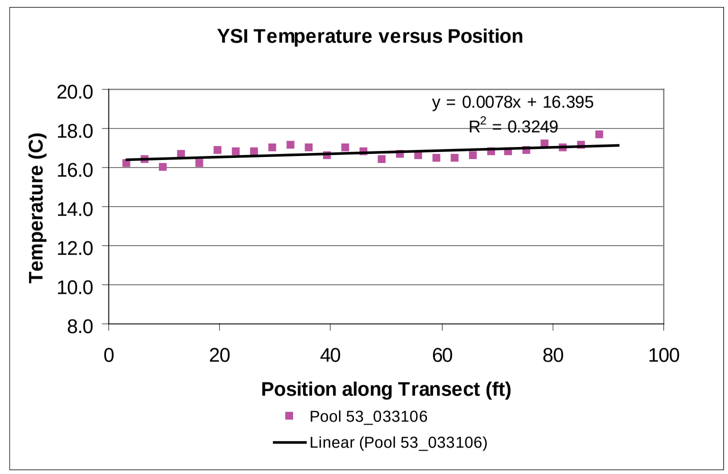


Figure 19. Regressions between temperature and position were significant for both pools on both days. Temperature (°C) was measured by YSI water quality meter. Position (ft) indicates the distance from the edge of the pool along the long axis. a) For Pool 29 on 3/17/2006, temperature versus position was highly significant with R2 = 0.850 and p <0.0008; b) for Pool 29 on 3/31/2006, temperature versus position was highly significant with R2 = 0.705 and p <0.0008; c) for Pool 53 on 3/17/2006, temperature versus position was highly significant with R2 = 0.798 and p <0.0008; and d) for Pool 53 on 3/31/2006, temperature versus position was significant with R2 = 0.325 and p = 0.0152.

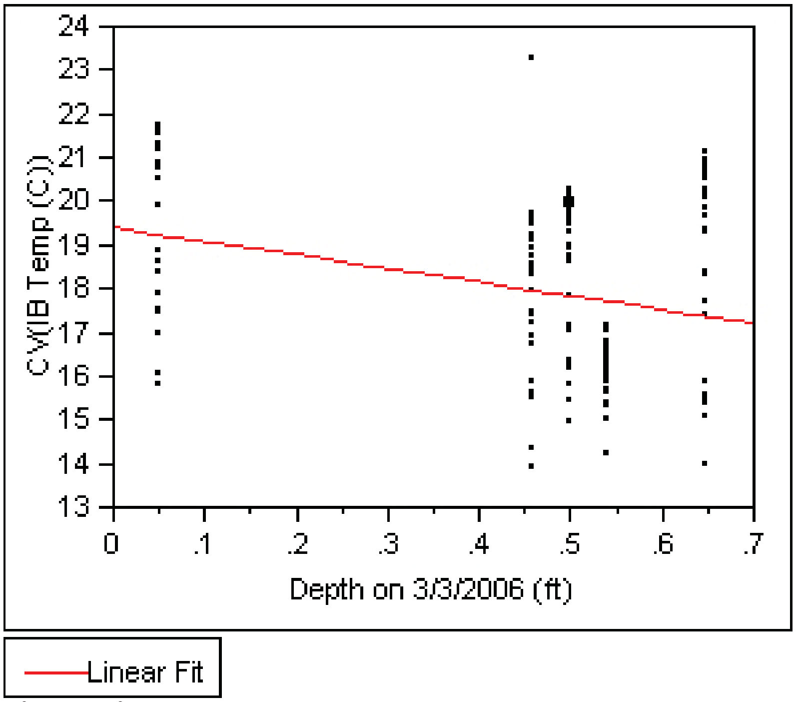
Y	X	R2	p
3/17 P29 Temperature	Position	0.850	<0.0008*
3/17 P29 pH	Position	0.955	<0.0008*
3/17 P29 Conductivity	Position	0.499	<0.0008*
3/17 P29 DO	Position	0.154	NS
3/17 P29 Temperature	Depth	0.519	<0.0008*
3/17 P29 pH	Depth	0.601	<0.0008*
3/17 P29 Conductivity	Depth	0.026	NS
3/17 P29 DO	Depth	0.137	NS
3/31 P29 Temperature	Position	0.705	<0.0008*
3/31 P29 pH	Position	0.697	<0.0008*
3/31 P29 Conductivity	Position	0.459	<0.0008*
3/31 P29 DO	Position	0.268	0.0152*
3/31 P29 Temperature	Depth	0.379	<0.0008*
3/31 P29 pH	Depth	0.623	<0.0008*
3/31 P29 Conductivity	Depth	0.511	<0.0008*
3/31 P29 DO	Depth	0.438	<0.0008*
3/17 P53 Temperature	Position	0.798	<0.0008*
3/17 P53 pH	Position	0.804	<0.0008*
3/17 P53 Conductivity	Position	0.131	NS
3/17 P53 DO	Position	0.493	<0.0008*
3/17 P53 Temperature	Depth	0.319†	0.0112*
3/17 P53 pH	Depth	0.319†	0.0112*
3/17 P53 Conductivity	Depth	0.031	NS
3/17 P53 DO	Depth	0.147	NS
3/31 P53 Temperature	Position	0.325†	0.0152*
3/31 P53 pH	Position	0.000	NS
3/31 P53 Conductivity	Position	0.066	NS
3/31 P53 DO	Position	0.213	NS
3/31 P53 Temperature	Depth	0.171	NS
3/31 P53 pH	Depth	0.000	NS
3/31 P53 Conductivity	Depth	0.135	NS
3/31 P53 DO	Depth	0.157	NS

*With Bonferroni correction: p value is multiplied by 8 (= 4 parameters x 2 tests)

† = Linear Fit

Table 4. Regression results for water quality parameters versus position showed that position explained water quality trends better than depth (i.e., stronger R2 values and more significant p values for position versus depth). Position (ft) indicates the distance from the edge of the pool along the long axis. Depth was measured as the water level above each sensor station during each site visit. All regression fits are polynomial (2°), unless otherwise marked († = linear fit). *All p values have Bonferonni correction for multiple parameter tests (p value is multiplied by 8 = 4 parameters x 2 tests).

Bivariate Fit of CV(IB Temp (C)) By Depth on 3/3/2006 (ft)



Linear Fit

CV(IB Temp (C)) = 19.427747 - 3.1225232 Depth on 3/3/2006 (ft)

Figure 20. Regression between CV of temperature (measured using I-Button sensors) versus depth was a poor fit (R2 = 0.0895), although significant (p = 0.0009). The CV captures the fluctuation in each temperature sensor station. Depth was measured as the water level above each sensor station on 3/3/2006, the date the sensors were deployed.

Figure 21a

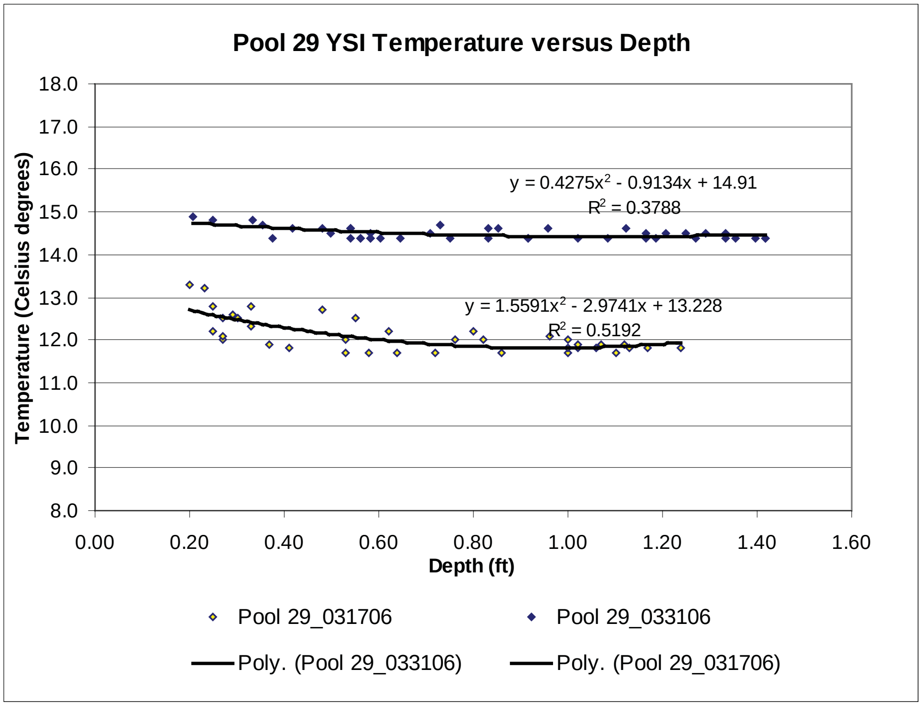


Figure 21b

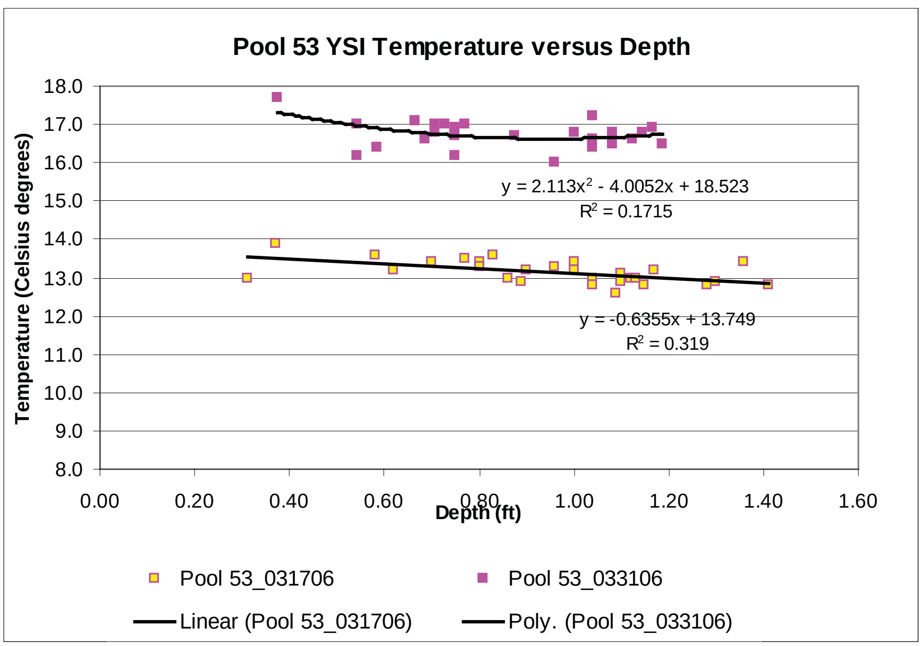


Figure 21. Regressions between temperature and depth were not as good of a fit as between temperature and position (Figure 19) and were not all significant. Temperature (°C) was measured by YSI water quality meter. Depth was measured as the water level above each sensor station during each site visit. a) For Pool 29 temperature versus depth was significant on 3/17/2006 and 3/31/2006, with R2 = 0.519 (p <0.0008) and R2 = 0.379 (p <0.0008.), respectively. b) For Pool 53 temperature versus depth was only significant on 3/17/2006 with R2 = 0.319 (p = 0.0112), and was not significant on 3/31/2006.

Relationships for other water quality parameters

Position explains pH better than depth, as determined from significant or higher R2 values from quadratic fit lines (Figures 22 and 23; Table 4). However, this relationship did not hold for Pool 53 on 3/31 when all pH values were 7.2, yielding a straight line with a slope of zero. Conductivity had a significant relationship to position but not to depth for Pool 29 on 3/17; the relationship was about the same between position and depth for Pool 29 on 3/31 (Figures 24 and 25; Table 4). Conductivity did not have a significant relationship with either position or depth for Pool 53 on 3/17 or on 3/31. Similarly, the relationship between DO and position versus depth did not show a clear trend: the relationship between DO and position or depth was not significant for Pool 29 on 3/17 or for Pool 53 on 3/31; for Pool 29 on 3/31 depth was a weak explanatory variable for DO and position was not significant; and for Pool 53 on 3/17 position was the stronger explanatory variable for DO and depth was not significant (Figures 26 and 27; Table 4).

Invertebrates

From dip net surveys, we found that numerous invertebrates were present in both Pool 29 and Pool 53 on all three survey dates (Table 5). Among large Branchiopods, California fairy shrimp (Linderiella occidentalis) was present in all surveys of both pools, while vernal pool fairy shrimp (Branchinecta lynchi) was only present in the 3/3 survey of Pool 29. Among the microcrustacea, water fleas (Cladocera), Copepods, and seed shrimp (Ostracods) were present in both pools, although Ostracods were not found during the 3/3 and 3/17 surveys of Pool 29. Among the aquatic insects, diving beetle larvae (Dytiscids) were only found in the 3/3 survey of Pool 29, midges (Chironomids) were found in all surveys of only Pool 29, water boat-men (Notonectids) were found in all surveys of Pool 53 and only the 3/31 survey of Pool 29, and other beetles (Coleoptera) were only found in the 3/31 survey of Pool 29. Among amphibians, abundant tadpoles were present during all three surveys in Pool 53. Tadpoles were conspicuously absent on all three survey dates from Pool 29. We identified Pacific treefrogs (Hyla regila) as the most abundant among the tadpoles in Pool 53. No other species of amphibians could be identified with certainty, although previous studies of the site have found Western spadefoot toad (Scaphiopus hammondi) tadpoles in Pool 53, in addition to Hyla regila tadpoles (Vollmar 2005).

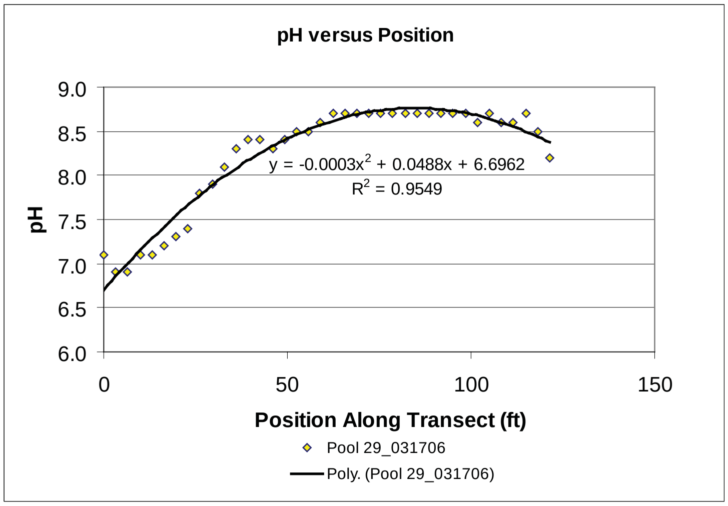


Figure 22a

Figure 22b

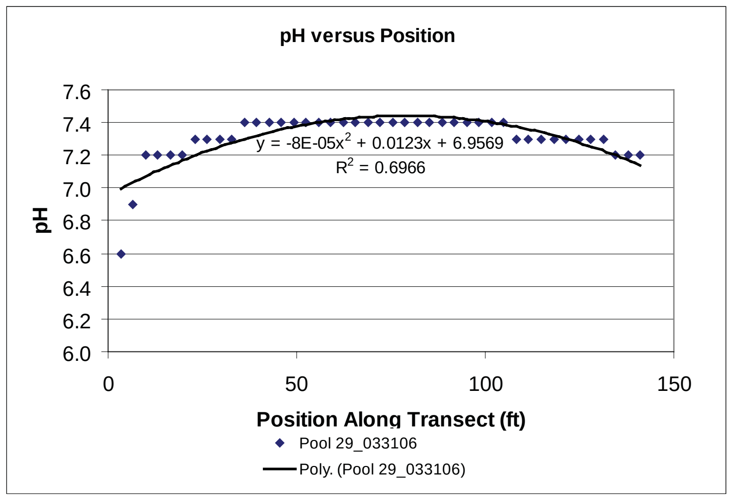


Figure 22c

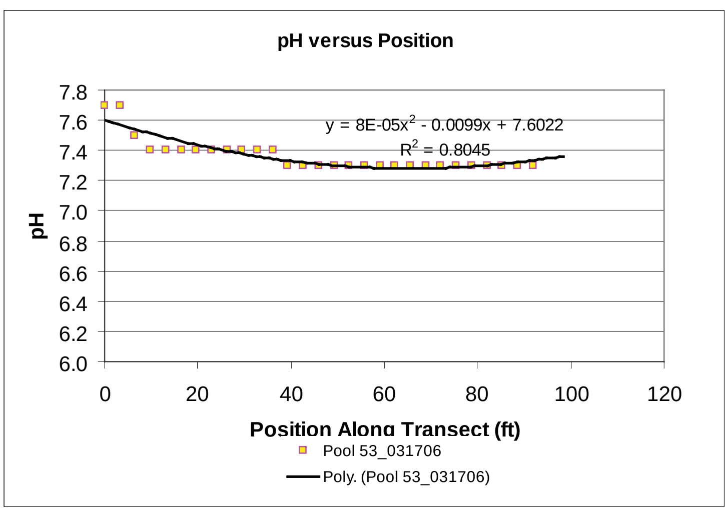


Figure 22. Regressions between pH and position were significant for both pools. Position (ft) indicates the distance from the edge of the pool along the long axis. a) For Pool 29 on 3/17/2006, pH versus position was highly significant with R2 = 0.955 and p <0.0008; b) for Pool 29 on 3/31/2006, pH versus position was highly significant with R2 = 0.697 and p <0.0008; and c) for Pool 53 on 3/17/2006, pH versus position was highly significant with R2 = 0.804 and p <0.0008. For Pool 53 on 3/31/2006, pH was 7.2 at all measurement points, and therefore the relationship between pH and position was not significant.

Figure 23a

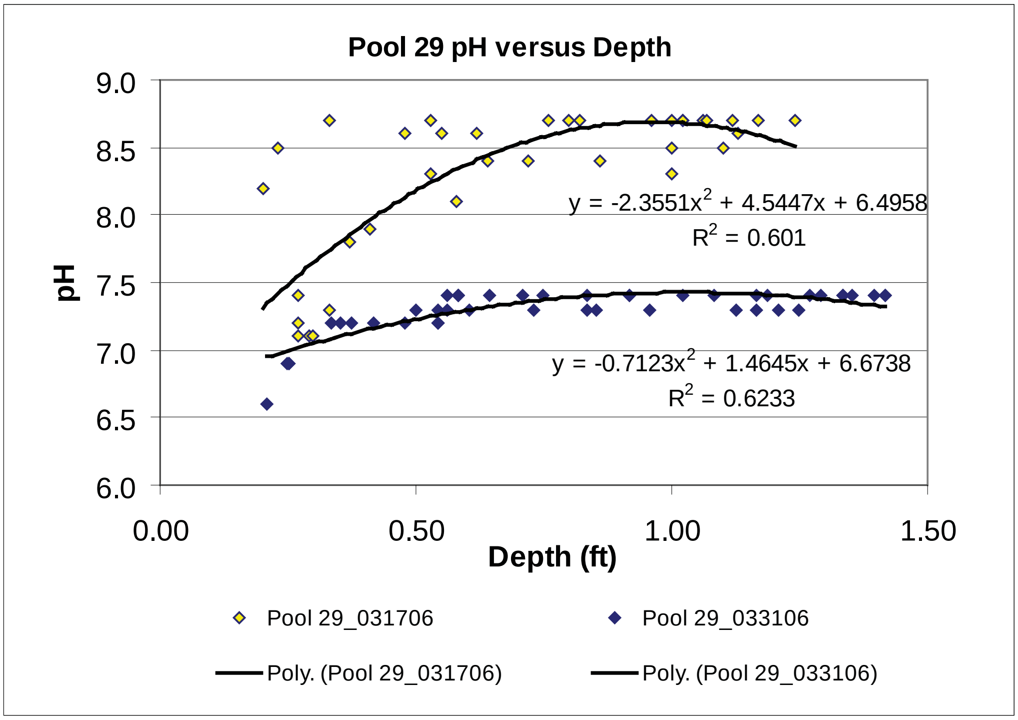


Figure 23b

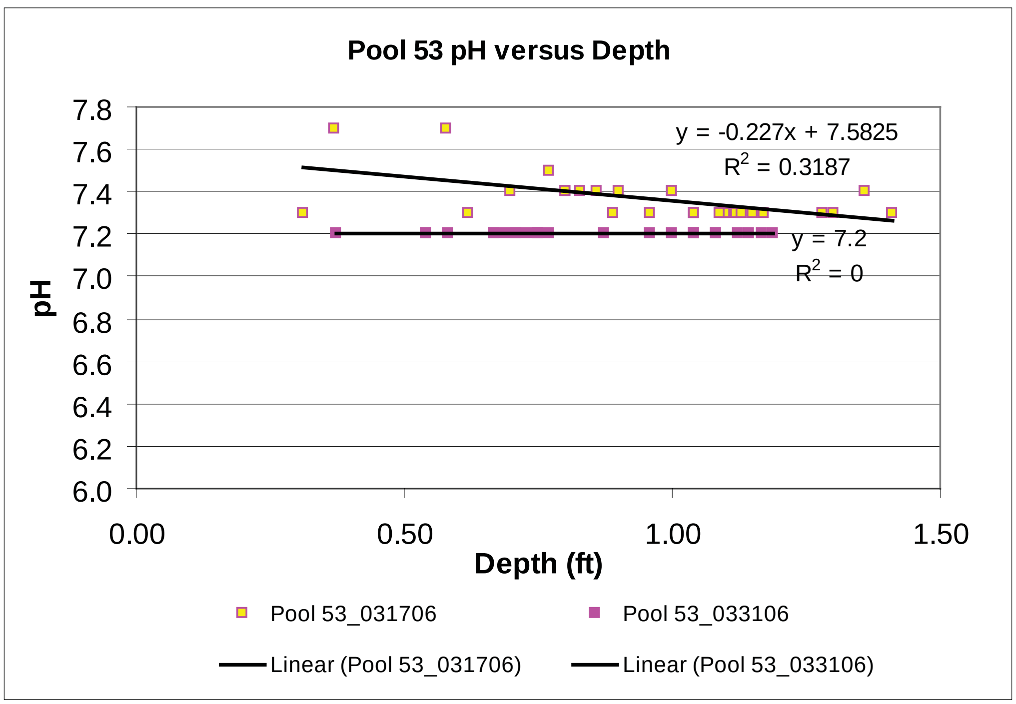


Figure 23. Regressions between pH and depth were not as good of a fit as between pH and position (Figure 22) and were not all significant. Depth was measured as the water level above each sensor station during each site visit. a) For Pool 29 pH versus depth was significant on 3/17/2006 and 3/31/2006 with R2 = 0.601 ($p < 0.0008$) and R2 = 0.623 ($p < 0.0008$), respectively. b) For Pool 53 pH versus depth was only significant on 3/17/2006 with R2 = 0.319 ($p = 0.0112$), and was not significant on 3/31/2006.

Figure 24a

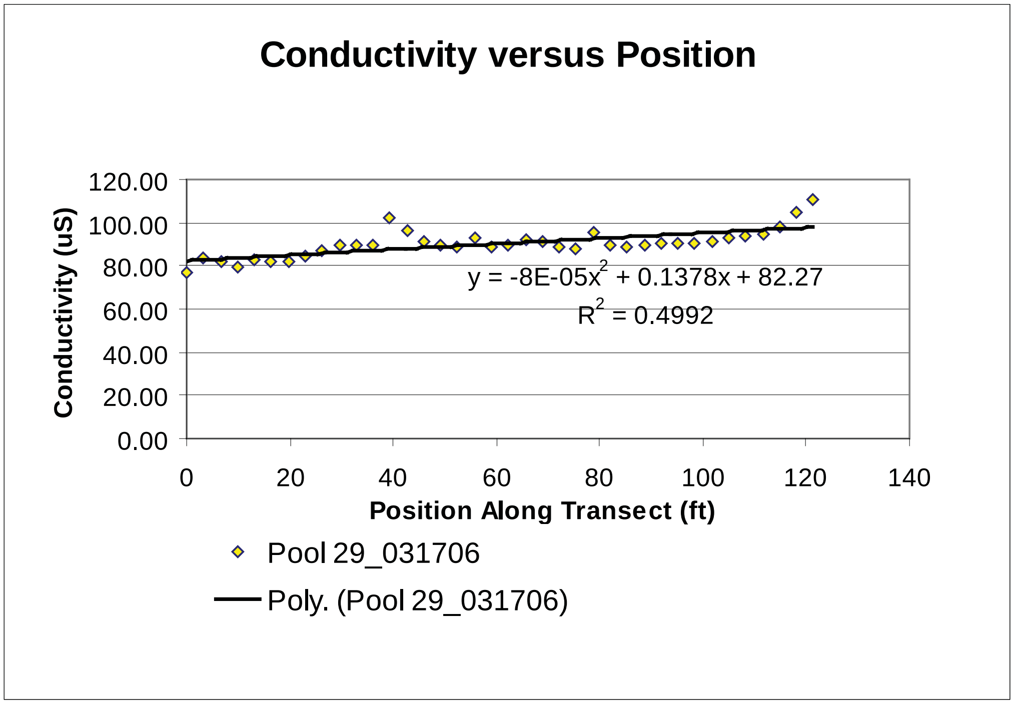


Figure 24b

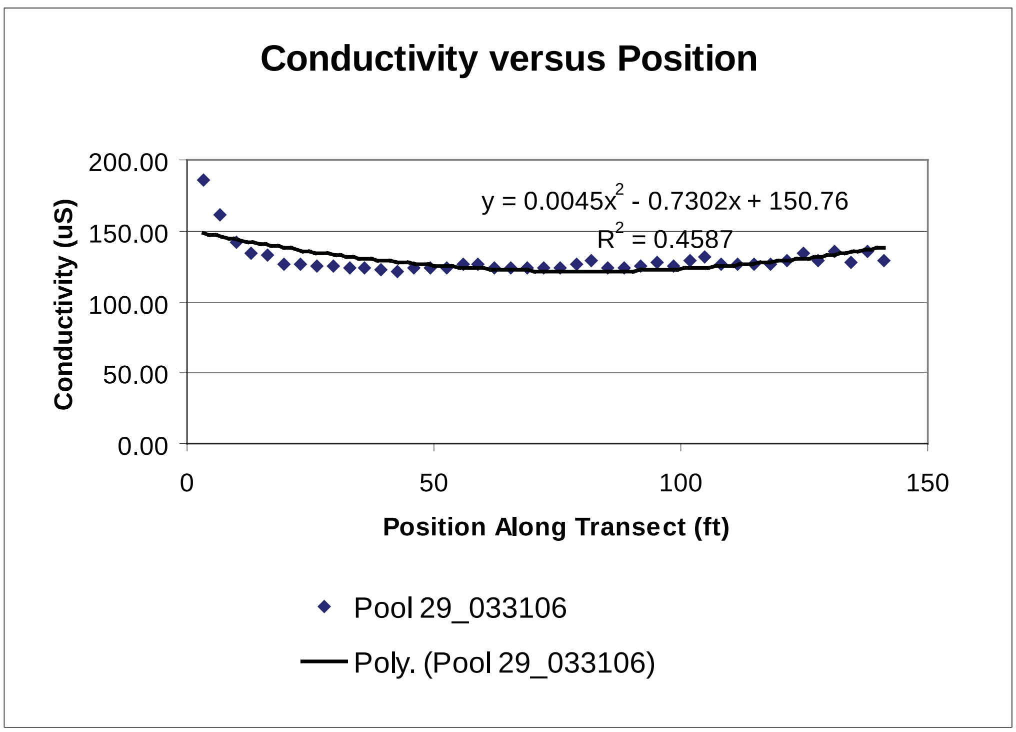


Figure 24. Regressions between conductivity and position were significant for Pool 29. Position (ft) indicates the distance from the edge of the pool along the long axis. a) For Pool 29 on 3/17/2006, conductivity versus position was significant with R2 = 0.499 and p <0.0008; and b) for Pool 29 on 3/31/2006, conductivity versus position was significant with R2 = 0.459 and p <0.0008. Conductivity versus position was not significant for Pool 53 on either day, therefore these figures were not included.

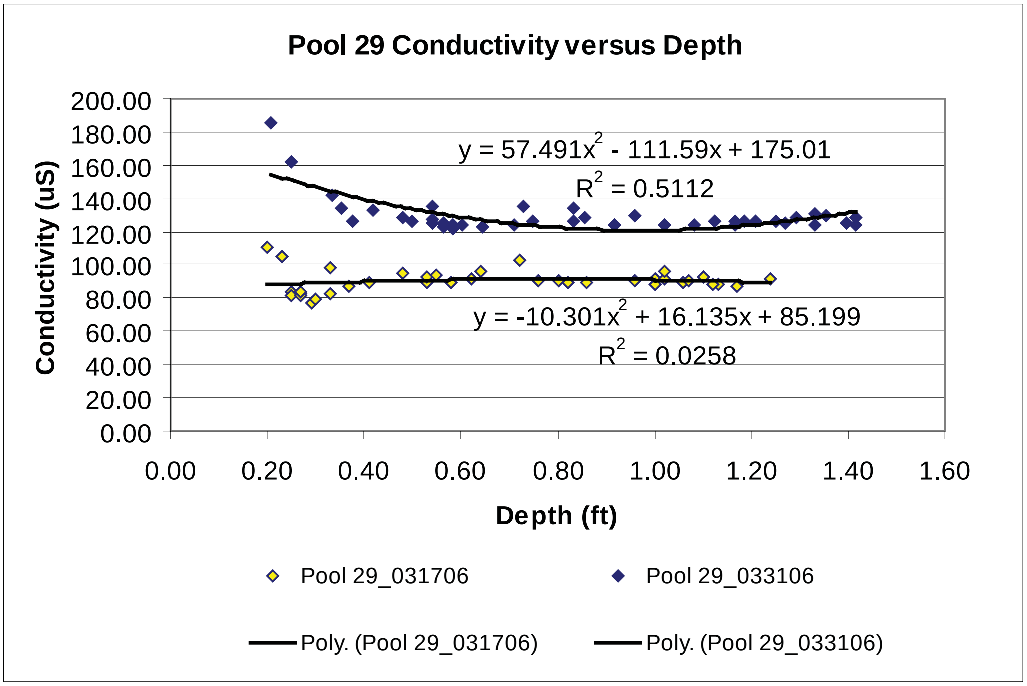


Figure 25. Regressions between conductivity and depth were not as good of a fit as between conductivity and position (Figure 24), and most were not significant. Depth was measured as the water level above each sensor station during each site visit. For Pool 29 conductivity versus depth was significant on 3/31/2006 with R2 = 0.511 and p <0.0008. For Pool 29 conductivity versus depth was not significant on 3/17/2006. Likewise, for Pool 53 conductivity versus depth was not significant on either day.

Figure 26a

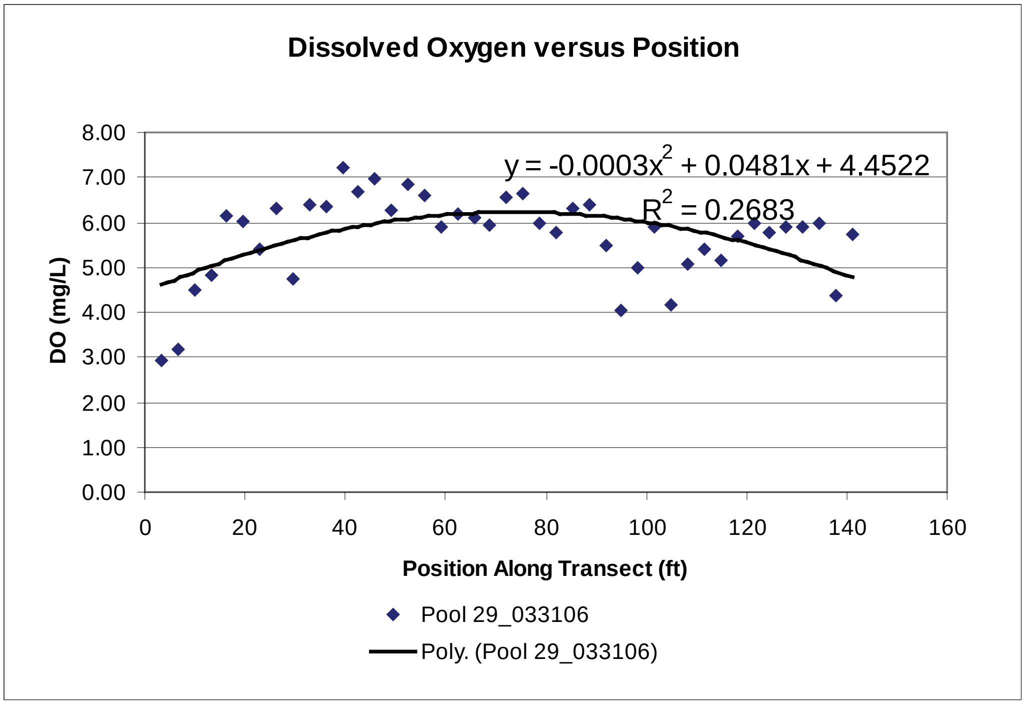


Figure 26b

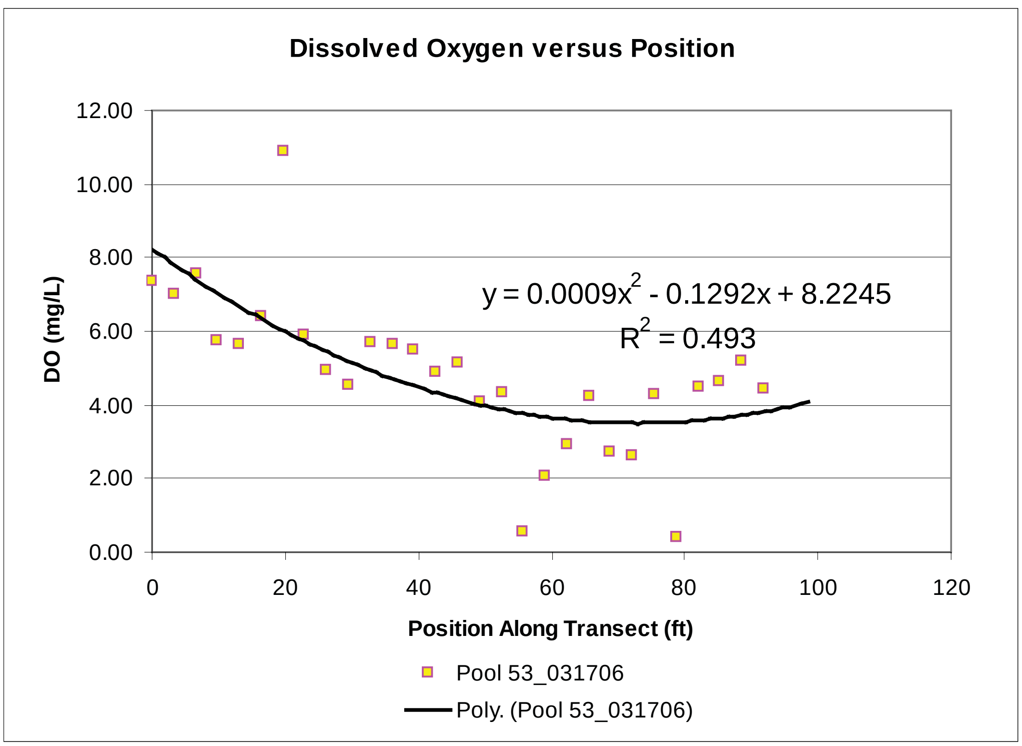


Figure 26. Regressions between dissolved oxygen (DO) and position were significant for Pool 29 and Pool 53. Position (ft) indicates the distance from the edge of the pool along the long axis. a) For Pool 29 on 3/31/2006, DO versus position was significant with R2 = 0.268 and p = 0.0152; but on 3/17/2006 DO versus position was not significant. b) For Pool 53 on 3/17/2006, DO versus position was significant with R2 = 0.493 and p <0.0008; but on 3/31/2006 DO versus position was not significant.

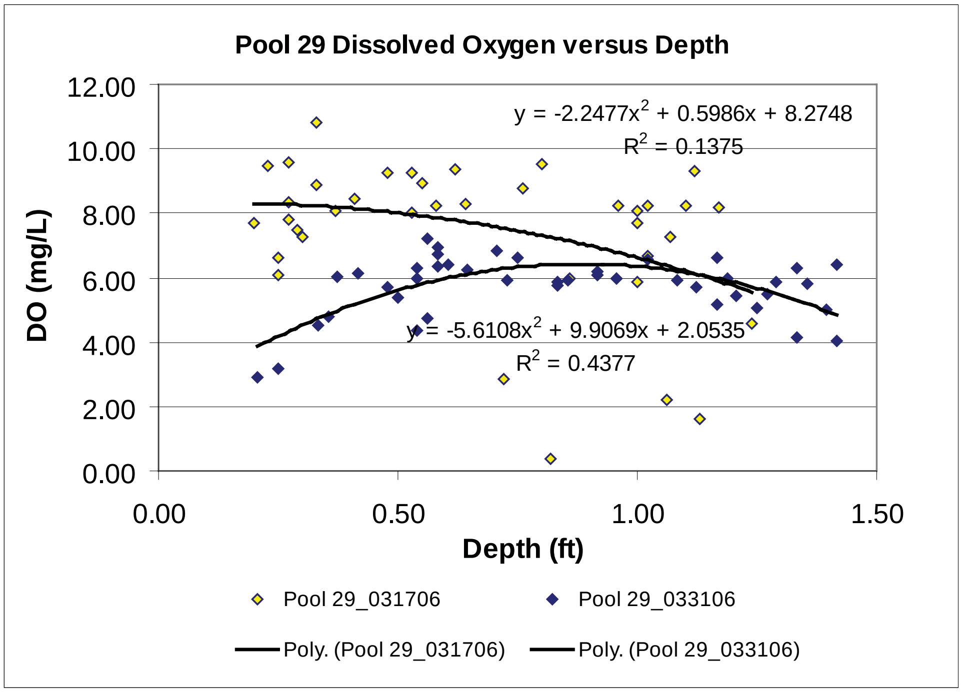


Figure 27. Regressions between dissolved oxygen (DO) and depth were not as good of a fit as between DO and position (Figure 26), and most were not significant. Depth was measured as the water level above each sensor station during each site visit. For Pool 29 DO versus depth was significant on 3/31/2006 with R2 = 0.438 and p <0.0008. For Pool 29 DO versus depth was not significant on 3/17/2006. Likewise, for Pool 53 DO versus depth was not significant on either day.

		Branchiopods		Microcrustacea			Aquatic Insects				Amphibians
Pool	Date	Linderiella Occidentalis	Branchinecta lynchi	Cladocera	Copepods	Ostracods	Dytiscids	Chironomids	Notonectids	Coleoptera	Tadpoles
29	2/10/2006	X	X	X	X		X	X			
29	3/17/2006	X		X	X			X			
29	3/31/2006	X		X	X	X		X	X	X	
53	2/10/2006	X		X	X	X			X		X
53	3/17/2006	no data									
53	3/31/2006	X		X	X	X			X		X
Note: “X” = present during dip net survey											

Table 5. Differences in aquatic community in Pool 29 and Pool 53 were detected by dipnet presence-absence surveys over three site visits. Pool 29 had two species of fairy shrimp and Pool 53 only had one. Pool 53 had amphibian tadpoles and Pool 29 did not.

Discussion

Although it is recognized that direct precipitation influences the morphological characteristics of vernal pools in general (Bauder 2005; Vollmar 2002; Keeley and Zedler 1998; Hanes and Stromberg 1998), we found that individual vernal pools can be quite different in their morphology, hydrology, and water quality in response to precipitation. For example, Pool 29 was a large pool with gradual slopes and a gently undulating bottom, while Pool 53 was smaller and deeper, with steeper slopes and a more undulating bottom. These morphological differences may have contributed to differences in hydrology and water quality conditions observed over the one month study period. For example, Pool 29 responded to increased precipitation by a large increase in pool surface area (almost five-fold) from 3/3 to 3/17, overtaking Pool 53 in surface area for the remainder of the study. On the other hand, Pool 53 responded to the same increased rainfall by a large increase in average depth from 3/3 to 3/17, much more so than the increase in average depth of Pool 29. For the 3/17 to 3/31 period, Pool 29 caught up to Pool 53 in average depth and continued to increase in area, but Pool 53 decreased in area over this period.

There are several possible explanations for these differences in pool hydrology in response to rainfall. Pool 53 is located adjacent to Highway 49 and was probably artificially created during the road construction. Bauder (2005) recognizes that artificial changes in a pool basin affect the hydrology of vernal pools, which could be the case for Pool 53. Because of its proximity to the roadway, there is also the potential that Pool 53 is connected to a roadway ditch or other drainage that may result in loss of water as was seen by the decrease in pool size from 3/17 to 3/31. Because Pool 29 is located on an unaltered section of the property, at the furthest boundary from any roads, it is unlikely that these same artificial conditions exist. Although both pools occur on the same 100-acre site, they have differences in underlying soils and geology: Pool 29 is a Ramona sandy loam located on the Turlock Lake formation, while Pool 53 is a Whitney and Rocklin sandy loam located on the Riverbank formation (Vollmar 2005) These differences in soil and geology may cause differences in their permeability and infiltration capacity, which could explain the decrease in surface water volume in Pool 53.

We would expect the differences in pool morphology and hydrology to be reflected in water quality, and if the differences are more permanent, also in aquatic community composition. Indeed, there were differences between the two pools in several water quality parameters: temperature, pH, DO, and conductivity. Although we expected the increase in temperature observed in both pools over the study period to be directly related to air temperature, this relationship was only significant for Pool 53. Also, average temperature was lower for Pool 53 than for Pool 29 over all three visits. For Pool 29 average pH increased from 3/3 to 3/17, while for Pool 53 average pH consistently decreased over the three visits. For Pool 29 average DO increased from 3/3 to 3/17, while for Pool 53 average DO stayed about the same over all visits. Dissolved oxygen is added to the water both by respiration from vegetation and mixing by wind. For Pool 29 average conductivity decreased from 3/3 to 3/17 while for Pool 53 conductivity only increased slightly from each visit to the next.

The observed trends in water quality parameters have several likely explanations. For example, a simple explanation for trends in pool temperature is based on the study method. Pool 53 was consistently measured later in the day, when sunlight was stronger; thus the longer radiant heating could explain Pool 53's higher average temperature. Temperature differences between the two pools will probably be negligible once the continuous data set is obtained from the sensors in Pool 29. However if temperature differences persist, another possible explanation may be differences in the surface area to volume ratio for the two pools (Keeley and Zedler 1998). Two possible explanations for the trends in pH are: 1) vernal pool soils are known to act as a weak buffer system for pH (Keeley and Zedler 1998) which may have kept Pool 29 increasing in pH as it expanded in area (over fresh soils); and 2) rain is acidic in pH (5.5) in the study region, and because Pool 53 increased dramatically in depth the buffer system was overwhelmed by acidic inputs which caused the pH to decrease. The trends in DO can be explained in a similar manner to those of pH: because Pool 29 increased in area over new surfaces this added vegetation inputs of DO to the pool; whereas Pool 53 increased in depth which limited both its capacity for wind mixing and sunlight for the growth of new vegetation. The trend in conductivity is more difficult to explain, but fits past observations for vernal pools that conductivity remains fairly constant during the rainy season and only changes markedly once the pools begin to dry and solutes become concentrated (Keeley and Zedler 1998).

The two pools also supported different aquatic communities. Pool 53 had amphibian tadpoles which were not present in Pool 29 over the one-month study period. Also, large branchiopods were more abundant in Pool 29, with two species found on the 3/3 visit, while only one species (and usually just one individual) was found in Pool 53 during all visits. Deeper pools hold water longer, influencing community composition (Keeley and Zedler 1998). This is true for Pool 53 which will remain wet for a longer period because of its steeper slopes and increased depth in response to increased rainfall. Pool 53 is a more suitable habitat for amphibians because they require a longer ponding period to complete their life cycle than many of the other shorter lived invertebrate species found in both pools. Likewise, amphibians may be absent in Pool 29 due to the pool's shallower depth and more gradual slopes, making it more dependent on rainfall for ponding. Pool 29 may dry out in less than average rainfall years, thus amphibians might opt to breed in a deeper site, such as Pool 53, that likely remains ponded for at least two months.

The differences in fairy shrimp diversity and abundance between the two pools may be explained by differences in turbidity. Although we did not measure turbidity, we observed that Pool 53 was clear and the bottom could be seen. Fairy shrimp may prefer higher turbidity (Eriksen and Belk 1999); Pool 29 is a very turbid, muddy pool, which could explain the greater diversity and abundance in fairy shrimp found in this pool. The other differences in water quality may have additional influences on aquatic community composition resulting in differences between the two pools. However, other significant differences were not detected, either because of the short study period or because of the survey methods used.

In addition to differences in hydrology and morphology, our short-term study data suggest that spatial temperature gradients exist in vernal pools. For example, the middle-pool temperature sensor (Station 6) had the least amount of fluctuation (lowest CV) and was the most different from all other stations (Tukey test), while those closest to the margin sorted together (i.e., were not significantly different) and showed some overlap with those at an intermediate distance from shore, which also sorted together. One possible explanation for such spatial temperature gradients is that there are microhabitats in the pool that have sufficiently different water quality conditions. For example, a complex pattern could exist in the pool where distinct regions or shelves have uniform conditions such as the margins as one set of conditions, intermediate distances from shore as another, and pool center as a third.

We found further support for microhabitats in vernal pools in our study of the relationships between water quality parameters versus position and depth. We expected a linear relationship between water quality parameters and depth (e.g. because we expect deeper water to be colder, and DO is known to decrease with increasing temperature, thus we expect DO to increase with depth). However, as shown by regression analyses, this relationship largely did not hold and position was found to be a better explanatory variable for temperature and pH. Conductivity and DO showed unclear patterns and most relationships for these two variables were not significant. These patterns for temperature and pH could occur because even at similar depths, microconditions exist that influence water quality parameters. For example, because the bottom of the vernal pool was found to have a strong microtopography—whether from cow activity or a geomorphic phenomenon—a depth of 0.5 ft could occur almost anywhere along the transect. This means that local conditions that influence water quality such as vegetation, soil, pool mixing by wind, heating from angle of sun, could be completely different at two sites each with a depth of 0.5ft. Whereas, almost regardless of depth, position on the long axis had less variability and followed a good polynomial fit.

Microhabitat theory may explain many of the relationships we found in our data including: the spatial gradient in temperature found in a small, but morphologically varying vernal pool (i.e., ANOVA and Tukey test); relationships of best fit between temperature and position were polynomial for both pools (i.e., parabola shaped fits mean temperature at the margins is lower than at the center); and the stronger relationships between position and temperature than between temperature and depth (i.e., higher R2 values and/or significant relationships). The phenomenon of microhabitats is well known for lotic systems such as rivers and streams (Hynes 1968; Ward and Stanford 1979), but not well documented for shallow lentic systems, with no literature on this for vernal pools. Thus our finding of a significant temperature distribution in a vernal pool and other evidence of microhabitats is new, and warrants further study.

Perhaps the most important consideration for our findings was the exceptional amount of precipitation that occurred during the study period. March 2006 was a rainy month both in comparison to other monthly data and to other March monthly data. This is important because the amount of precipitation on the site likely created more, larger, and deeper pools than usual (Bauder 2005; Keeley and Zedler 1998). It is recognized that such significant differences in precipitation between years and the intra-year differences in the pattern and intensity of storms causes unpredictability for vernal pools (Bauder 2005). Therefore, many of the inter-pool differences found in this study (morphology, hydrology, water quality, and aquatic community) and even the intra-pool differences (spatial temperature gradients and other evidence of microhabitats) may not hold for other water years, or may be more subdued.

Conclusion

We found that two individual vernal pools exhibited differences in their morphology and hydrology over a one-month study period. Additionally, we found that a spatial temperature gradient existed over the same period in one vernal pool on our study site in Madera County, California. This finding and other evidence that microhabitats may exist in vernal pools has important implications regarding potential influences on fairy shrimp cyst hatching. For example, it is well known that only part of the total cyst seed bank will hatch out in any given year (Simovich and Hathaway 1997, Philippi et al. 2001, Ripley et al. 2004), which to date has been attributed entirely to ecological adaptation of branchiopods to the unpredictable inundation regimes of vernal pools. However, cysts may hatch at differential rates or only in a certain distribution in a pool based on microhabitats such as temperature and pH gradients. Equally likely, cysts may rely on one set of conditions for hatching but quickly migrate to another microhabitat within the pool for the most favorable conditions that support the next life phase. Thus, it is important that vernal pool mitigation efforts recreate the microtopography found in vernal pools basins because this topography may be a critical factor in creating the gradient of water quality conditions which may be required for aquatic life.

More robust studies are needed to fully test the findings of this study, especially as they relate to water quality gradients and microhabitats and the interactions of these with the fauna of vernal pools. In the short term we plan to retrieve the temperature sensors from Pool 29 when the basin dries and compare the data to Pool 53. If Pool 29 also exhibits a spatial temperature gradient this would provide additional support for our microhabitat hypothesis because Pool 29 was shown to have a different morphology (in particular, a less undulating pool bottom) and hydrology. Wendy plans to extend this study for a whole season and in more pools at the same site to keep the differences in soil type, rainfall, temperature, and photoperiod as uniform as possible, while further exploring the inter-pool morphology and hydrology differences, and the intra-pool water quality differences revealed by this study. Other water quality parameters including turbidity also merit further study as they relate to differences in aquatic communities. Eventually, additional sites around California could be incorporated to test significant ecological findings at this site as they relate to a variety of vernal pool habitats, including both natural and created pools.

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APPENDIX A

Summary tables for rainfall and air temperature regressions

Bivariate Fit of Pool 29 Area (ft2) By Precip Cum (2 wks prior) (in)

Summary of Fit

RSquare	0.99379
RSquare Adj	0.987579
Root Mean Square Error	661.3117
Mean of Response	9258
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	69983115	69983115	160.0224
Error	1	437333	437333.18	Prob > F
C. Total	2	70420448		0.0502

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2903.236	1034.406	-2.81	0.2179
Precip Cum (2 wks prior) (in)	8367.8228	661.4881	12.65	0.0502

Bivariate Fit of Pool 53 Area (ft2) By Precip Cum (2 wks prior) (in)

Summary of Fit

RSquare	0.776192
RSquare Adj	0.552384
Root Mean Square Error	648.6297
Mean of Response	3700.667
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1459108.2	1459108	3.4681
Error	1	420720.5	420721	Prob > F
C. Total	2	1879828.7		0.3137

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1944.6654	1014.569	1.92	0.3061
Precip Cum (2 wks prior) (in)	1208.2577	648.8028	1.86	0.3137

Bivariate Fit of Pool 29 Avg Depth (ft) By Precip Cum (2 wks prior) (i

Summary of Fit

RSquare	0.629686
RSquare Adj	0.259371
Root Mean Square Error	0.127744
Mean of Response	0.676667
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	0.02774815	0.027748	1.7004
Error	1	0.01631852	0.016319	Prob > F
C. Total	2	0.04406667		0.4165

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4345091	0.199814	2.17	0.2744
Precip Cum (2 wks prior) (in)	0.1666222	0.127778	1.30	0.4165

Bivariate Fit of Pool 53 Avg Depth (ft) By Precip Cum (2 wks prior) (i

Summary of Fit

RSquare	0.996507
RSquare Adj	0.993015
Root Mean Square Error	0.01617
Mean of Response	0.723333
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	0.07460519	0.074605	285.3268
Error	1	0.00026147	0.000261	Prob > F
C. Total	2	0.07486667		0.0376

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.3262647	0.025293	12.90	0.0493
Precip Cum (2 wks prior) (in)	0.2732124	0.016174	16.89	0.0376

Bivariate Fit of Pool 29 Avg Temp (C) By Precip Air Temp avg (F)

Summary of Fit

RSquare	0.972553
RSquare Adj	0.945107
Root Mean Square Error	0.585888
Mean of Response	12.03333
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	12.163401	12.1634	35.4344
Error	1	0.343265	0.3433	Prob > F
C. Total	2	12.506667		0.1060

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-17.66327	5.000232	-3.53	0.1756
Precip Air Temp avg (F)	0.6102041	0.102509	5.95	0.1060

Bivariate Fit of Pool 53 Avg Temp (C) By Precip Air Temp avg (F)

Summary of Fit

RSquare	0.999787
RSquare Adj	0.999574
Root Mean Square Error	0.060609
Mean of Response	13.63333
Observations (or Sum Wgts)	3

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	17.242993	17.2430	4693.926
Error	1	0.003673	0.0037	Prob > F
C. Total	2	17.246667		0.0093

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-21.72449	0.517265	-42.00	0.0152
Precip Air Temp avg (F)	0.7265306	0.010604	68.51	0.0093

Bivariate Fit of Avg Daily Temp (C) By Precip Air Temp avg (F)

Summary of Fit

RSquare	0.741151
RSquare Adj	0.731564
Root Mean Square Error	1.02687
Mean of Response	12.70782
Observations (or Sum Wgts)	29

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	81.51831	81.5183	77.3080
Error	27	28.47047	1.0545	Prob > F
C. Total	28	109.98878		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-5.642822	2.095773	-2.69	0.0120
Precip Air Temp avg (F)	0.3677737	0.041828	8.79	<.0001

APPENDIX B

Summary tables for temperature differences

Temperature Differences by Date: Oneway Anova

Summary of Fit

Rsquare	0.219252
Adj Rsquare	0.196945
Root Mean Square Error	6.909706
Mean of Response	14.89596
Observations (or Sum Wgts)	145

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
IB Station	4	1877.0630	469.266	9.8288	<.0001
Error	140	6684.1651	47.744		
C. Total	144	8561.2282			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	29	16.2260	1.2831	13.689	18.763
2	29	12.7570	1.2831	10.220	15.294
5	29	16.6686	1.2831	14.132	19.205
6	29	9.1808	1.2831	6.644	11.718
8	29	19.6475	1.2831	17.111	22.184

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.76365	0.05

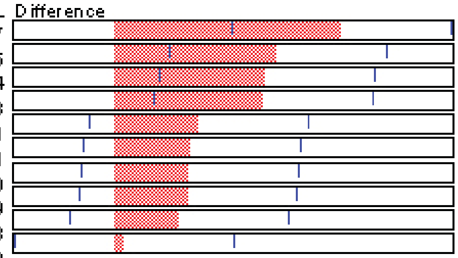
Abs(Dif)-LSD	8	5	1	2	6
8	-5.0149	-2.0360	-1.5933	1.8756	5.4518
5	-2.0360	-5.0149	-4.5723	-1.1033	2.4729
1	-1.5933	-4.5723	-5.0149	-1.5459	2.0303
2	1.8756	-1.1033	-1.5459	-5.0149	-1.4386
6	5.4518	2.4729	2.0303	-1.4386	-5.0149

Positive values show pairs of means that are significantly different.

Level				Mean
8	A			19.647478
5	A	B		16.668567
1	A	B		16.225951
2		B	C	12.757019
6			C	9.180778

Levels not connected by same letter are significantly different

Level	- Level	Difference	Lower CL	Upper CL	Difference
8	6	10.46670	5.45183	15.48157	
5	6	7.48779	2.47292	12.50265	
1	6	7.04517	2.03031	12.06004	
8	2	6.89046	1.87559	11.90533	
5	2	3.91155	-1.10332	8.92641	
2	6	3.57624	-1.43863	8.59111	
1	2	3.46893	-1.54593	8.48380	
8	1	3.42153	-1.59334	8.43639	
8	5	2.97891	-2.03595	7.99378	
5	1	0.44262	-4.57225	5.45748	



Temperature Differency by Hour: Oneway Anova

Summary of Fit

Rsquare	0.296073
Adj Rsquare	0.271589
Root Mean Square Error	1.833837
Mean of Response	18.05384
Observations (or Sum Wgts)	120

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
IB Station	4	162.66387	40.6660	12.0923	<.0001
Error	115	386.74026	3.3630		
C. Total	119	549.40413			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	24	18.3145	0.37433	17.573	19.056
2	24	17.7815	0.37433	17.040	18.523
5	24	18.6077	0.37433	17.866	19.349
6	24	16.0247	0.37433	15.283	16.766
8	24	19.5409	0.37433	18.799	20.282

Std Error uses a pooled estimate of error variance

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

q*	Alpha
2.77154	0.05

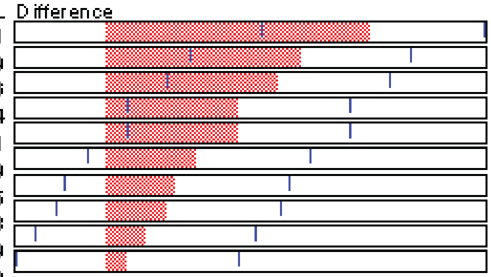
Abs(Dif)-LSD	8	5	1	2	6
8	-1.4672	-0.5340	-0.2408	0.2922	2.0490
5	-0.5340	-1.4672	-1.1740	-0.6410	1.1158
1	-0.2408	-1.1740	-1.4672	-0.9342	0.8226
2	0.2922	-0.6410	-0.9342	-1.4672	0.2896
6	2.0490	1.1158	0.8226	0.2896	-1.4672

Positive values show pairs of means that are significantly different.

Level				Mean
8	A			19.540864
5	A	B		18.607702
1	A	B		18.314479
2		B		17.781474
6			C	16.024667

Levels not connected by same letter are significantly different

Level	- Level	Difference	Lower CL	Upper CL	Difference
8	6	3.516196	2.04899	4.983401	
5	6	2.583035	1.11583	4.050239	
1	6	2.289812	0.82261	3.757016	
8	2	1.759390	0.29219	3.226594	
2	6	1.756807	0.28960	3.224011	
8	1	1.226385	-0.24082	2.693589	
8	5	0.933161	-0.53404	2.400365	
5	2	0.826229	-0.64098	2.293433	
1	2	0.533005	-0.93420	2.000209	
5	1	0.293223	-1.17398	1.760428	



Temperature versus depth: Summary of Fit

RSquare	0.089529
RSquare Adj	0.081813
Root Mean Square Error	2.058913
Mean of Response	18.05384
Observations (or Sum Wgts)	120

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	49.18756	49.1876	11.6032
Error	118	500.21657	4.2391	Prob > F
C. Total	119	549.40413		0.0009

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.427747	0.44498	43.66	<.0001
Depth on 3/3/2006 (ft)	-3.122523	0.916676	-3.41	0.0009