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Final Report

Ecological Assessment of a Wetlands Mitigation Bank (Phase IV: Post-Restoration)

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16. Abstract

The overall objective for the Tulula Wetlands Mitigation Bank was to restore the functional and structural characteristics of a mountain stream and the adjacent alluvial wetlands. Specific restoration objectives of this study included: 1) determining the success of stream realignment by evaluating the geomorphology of a new channel before and after water release, 2) evaluating the responses of vegetation and soil microfauna to different hydrologic regimes and to the disturbance created by restoration, and 3) evaluating wildlife use of the site in response to changing hydrologic conditions (amphibians) and plant community succession (birds). A meandering channel (8,500 linear feet in length) was constructed across the floodplain and water was released into the new channel in 2001 and 2002. Eight random channel segments were used for measurements of stream geomorphology and after four years of water flow few differences were noted for channel pattern, although changes were observed for cross-sectional areas of riffles and pools. Isolated areas of bank and bed erosion were noted. The hydrology of Tulula has been influenced by the stream restoration, with most notable differences occurring for areas within 75 ft of the channel. Beaver influenced the hydrology of the lower end of the site more so than stream restoration. The higher water table increased the establishment of tag alder, an important N-fixing shrub species. However, restoration activities disrupted the soil profile, leading to lower reproductive success of alder. Recently disturbed areas at Tulula had lower decomposition rates and fewer litter microarthropods compared to older plant communities. Data collected from 1996-2006 indicate that constructed ponds are of higher quality than reference ponds based on physiochemical characteristics, seasonal hydroperiod, and use by resident amphibians. Amphibians rapidly colonized constructed vernal ponds, and the number of species that utilize these as breeding sites averaged about 40% higher than that of reference ponds. The survivorship and output of wood frog and spotted salamander juveniles have declined since pond construction, in part due to the accumulation of predators in ponds, the outbreak of a virus pathogen, and premature pond drying associated with drought. Breeding bird surveys in 2006 indicated that 30 species of birds were likely breeding on site, which was similar to the number likely breeding in 2004 and to pre-restoration levels in 1994 and 1998. The relative abundance of birds in 2006 increased 14% from 2004, but was 28% and 41% less than pre-restoration levels in 1994 and 1998. Overall, the species composition of birds has changed from pre-restoration years, with generalist species and species associated with water, becoming more common, while species associated with early-successional habitats, including many neotropical migrants of conservation concern, including Golden-winged Warbler, Kentucky Warbler, Swainson's Warbler, White-eyed Vireo, and Yellow-breasted Chat, have dramatically declined. Reasons for these changes are attributed to the loss of early-successional habitats due to flooding by beaver and natural succession.

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EXECUTIVE SUMMARY

Our overall goal was to document the ecological success of the wetlands at the Tulula Wetlands Mitigation Bank (Graham County) in response to restored hydrology, soils, and vegetation. We collected data on the structural and functional attributes at Tulula for twelve years, including seven years of baseline data before large-scale restoration was initiated. This presented a unique opportunity to evaluate the ecology of Tulula relative to most wetland restoration projects, which tend to compare post-restoration data with a year or two of pre-restoration data to determine restoration success. Our data should provide NCDOT an ecological assessment that may be useful for evaluating other wetland restoration projects located throughout the state. The following objectives provide the framework for a comprehensive ecological assessment of the restored wetlands of Tulula: 1) determine the success of stream realignment by evaluating the geomorphology of the new channel before and after water is introduced, 2) evaluate the responses of vegetation and soil microfauna to different hydrologic regimes and to the disturbance created by restoration, and 3) evaluate wildlife use of the site in response to changing hydrologic conditions (amphibians) and plant community succession (birds).

A primary focus of restoration at Tulula was to improve site hydrology. A meandering channel (8,500 linear feet in length) was constructed across the floodplain in five separate sections that were connected in fall 2001 and summer 2002. Eight random channel segments were used for measurements of stream geomorphology, including sinuosity, cross-sectional areas of riffles and pools, bank slope, slope of the water surface, and overall channel configuration. After four years of water flow, differences were noted in certain aspects of channel morphology, and localized areas of erosion were noted with erosion control pins and through increases in the cross-sectional areas of some riffles and pools. However, the overall configuration of the channel was maintained over the four-year period.

The restoration of hydrology at Tulula was evaluated primarily by changes in water-table depth as recorded with a series of electronic and manual wells. Our assumption was that the overall water table of the site would rise after the channel was restored and the drainage ditches were plugged. We found that the hydrology of Tulula was influenced by these restoration efforts, with most changes occurring in water-table wells located near the stream channel. Restoration appeared to have little influence on the hydrology of the fen or of areas located farther from the channel. Beaver dams had more of an influence on site hydrology at the lower end of the site than channel restoration.

Disturbance of the soil profile by earth-moving equipment during restoration at Tulula disrupted the soil profile, resulting in lower levels of soil carbon and nitrogen in a restored area with a low water table. Nitrogen-fixing tag alders that colonized this area showed lower sexual and asexual reproductive success. Wet soils appeared to favor the establishment of a large number of tag alders, although the basal diameter of these plants was smaller than that of plants growing in less-crowded, drier soils. Herbivore damage was more pronounced on tag alder leaves from wet soils, although leaf damage was not correlated with levels of leaf carbon or nitrogen. Sap-feeding insect herbivores were noted in both wet and dry areas, with little difference noted in the levels of infestation.

Measurements of soil pH and organic carbon indicate that for soils, decomposition rates and high total microarthropod numbers are functions of an older, less disturbed, ecosystem. These findings could be related to the presence of a canopy in the red maple forest and the closed fen,

protecting litter-dwelling arthropods from extremes in temperature and from desiccation when exposed to solar radiation. However, the low numbers of total microarthropods in open areas of the Tulula floodplain, compared to sites with more canopy even before leaves are present, indicates that other factors are involved. We posit that soil disturbance decreases the abundance of litter microarthropods, a critical ecosystem factor.

Ten ponds were constructed in 1995-1996 to replace natural breeding sites that were destroyed during golf course construction. Data collected from 1996-2006 indicate that constructed ponds are of higher quality than reference ponds based on physiochemical characteristics, seasonal hydroperiod, and use by resident amphibians. The reference ponds progressively deteriorated between 1996-2002 with respect to seasonal hydroperiod, but improved in quality after 2002 in association with beaver activity and average to above average rainfall. In 2002 the majority either did not fill or dried prematurely, resulting in catastrophic mortality of pond populations. The hydroperiod of most constructed ponds appears to be ideal for most vernal pond breeders between 1996-2002. Seven of 10 ponds underwent seasonal drying in most years, typically in late summer or fall after larvae had metamorphosed. However, fish have colonized many ponds since 2002 in association with above normal rainfall, beaver activity, and completion of the final phase of reconstruction.

Amphibians rapidly colonized the constructed ponds, and the number of species that utilize these as breeding sites averaged about 40% higher than that of reference ponds. The survivorship and output of juveniles of two focal species (wood frog; spotted salamander) have declined since pond construction, in part due to the accumulation of predators in ponds, the outbreak of a virus pathogen, and premature pond drying associated with drought. Nonetheless, a small percentage of ponds on site have successfully produced juveniles annually, and populations of both species are being maintained at viable levels.

In 2006, 30 species of birds were likely breeding on site. The number of species breeding in 2006 was similar to that in 2004 and to pre-restoration levels in 1994 and 1998. The relative abundance of birds in 2006 increased 14% from 2004, with a 103 total observations. However, the abundance of birds in 2006 was 28% and 41% less than pre-restoration levels in 1994 and 1998. Overall, the composition of bird species has changed substantially from pre-restoration years; generalist species and species associated with water, including Song Sparrow, Tufted Titmouse, and Red-winged Blackbird, have become more abundant, while species associated with early-successional habitats, including many neotropical migrants of conservation concern such as the Golden-winged Warbler, Hooded Warbler, Kentucky Warbler, Swainson's Warbler, White-eyed Vireo, and Yellow-breasted Chat, have become less abundant.

The changes (pre- vs. post-restoration) observed in the overall species composition and the decrease in relative abundance of birds at Tulula are attributed primarily to the loss of early-successional habitats due to flooding by beaver and natural succession. Areas inundated with water (approximately one-third of the floodplain) and areas dominated by single-aged stands of saplings reduced the habitat productivity of birds, by decreasing the amounts of herbaceous and shrub layers, thereby reducing the diversity of the habitat structure and amount of edge. Management intervention is needed in order to restore the productivity of the habitat for birds. Management objectives should include taking appropriate actions to control the flooding caused by beaver, and maintaining a variety of early-successional habitat types throughout the site.

I. INTRODUCTION

Surface transportation projects such as highway construction often impact wetland resources and cause unavoidable losses of small wetland areas. Increasingly, wetland losses are being mitigated by the creation of "banks" of restored or natural wetlands that are protected from future disturbance. Mitigation banks allow the consolidation of efforts to mitigate for cumulative wetland losses, facilitate advanced planning, and enhance the monitoring and evaluation of mitigation projects (Short 1988). The Tulula Wetland Mitigation Bank was created to offset impacts of highway projects in western North Carolina, particularly in the Little Tennessee River basin (1,158,883 ac) located in Macon, Swain, Graham, Jackson, Clay, and Transylvania Counties. The site was ideal for establishing a mitigation bank in the mountains of North Carolina because of its relatively large size (235 ac) and its need for large-scale restoration.

The Tulula Wetland Mitigation Bank (Tulula) (35^{o}17'N, 83^{o}41'W) is located in Graham County, NC in the floodplain of Tulula Creek, 7.7 miles west of Topton. The site covers approximately 235 ac at an elevation ranging from 2500 to 2800 ft. It is characterized by a relatively large, level floodplain along Tulula Creek, and is bordered by forested uplands and infrequent seepage communities on adjacent slopes. A complete description of vegetative communities at Tulula is found in Moorhead et al. (2001a). Tulula was part of the Nantahala National Forest and owned by the U.S. Forest Service until the mid-1980's, when it was traded to a group of developers for commercial development of a golf course. During construction of the golf course, the bed of Tulula Creek was dredged and channelized and several drainage ditches were dug. Spoil from the drainage ditches and from 11 small golf ponds was spread over portions of the floodplain. A large portion of the floodplain forest was removed during the construction of 18 fairways. About 40% of the wetlands were disturbed by drainage and timber harvest during golf course construction.

Tulula was purchased in 1994 by the North Carolina Department of Transportation (NCDOT) to develop a wetlands mitigation bank. We began collecting information on baseline ecological conditions in 1994 (soils, hydrology, flora, and fauna) and have evaluated restoration activities at the site since 1995 (see www.unca.edu/tulula for details and species lists).

Assessing the success of wetland restoration projects requires an evaluation of ecosystem structure and function. Long-term success is rarely documented, and failure is common for a variety of reasons. Our goal was to document the ecological success of the wetlands at Tulula in response to restored hydrology, soils, and vegetation. Our data should provide NCDOT an ecological assessment that may be useful for evaluating other wetland restoration projects located throughout the state.

The following objectives provide the framework for a comprehensive ecological assessment of the restored wetlands of Tulula: 1) determine the success of stream realignment by evaluating the geomorphology of the new channel before and after water is introduced,
2) following restoration of site hydrology, evaluate the responses of vegetation and soil microfauna to different hydrologic regimes and to the disturbance created by restoration, and 3) evaluate wildlife use of the site in response to changing hydrologic conditions (amphibians) and plant community succession (birds).

II. RESEARCH METHODS AND RESULTS

Ecological conditions at Tulula have been documented for over twelve years by UNCA (see www.unca.edu/tulula, North Carolina Department of Transportation 1997, Rossell et al. 1999, Moorhead et al. 2001a, Moorhead et al. 2001b, Moorhead et al. 2002, Moorhead et al. 2004). Projects completed at Tulula but not covered in this report are listed in Appendix G. Ecological success of wetlands restoration at Tulula has been evaluated by comparing the extensive pre-restoration database to the post-restoration data.

A. Stream Restoration and Hydrology

1. Stream Restoration

A primary focus of restoration at Tulula was to improve site hydrology. A meandering channel (8,500 linear feet in length) was constructed across the floodplain during the winter of 1999/2000. The design of the new channel was based partially on the physical characteristics of a relic channel found primarily at the lower end of the site. The relic channel was used, when practical, as part of the new meandering channel. The channel was re-constructed in 2001/2002 to correct problems associated with longitudinal grade. Common streambank erosion techniques, such as fiber matting, coir fiber rolls, root wads, and live stakes of willow (*Salix* spp.) and silky dogwood (*Cornus amomum*), were installed to improve the short-term stability of the new channel. Four sections of the constructed channel, in the upper and middle portions of the site, were joined together by crossing the dredged channel of Tulula Creek in fall 2001. The fifth section was connected in two stages in May (Section V) and June (Section Va) 2002. The design criteria used to construct the channel are shown in Table 1.

Methods

A primary objective for restoration efforts at Tulula was to determine the success of stream realignment by evaluating the geomorphology of the new channel before and after water introduction. Eight random channel segments were chosen in the five stream sections that were restored in 2001/2002. Each segment included four to six riffle-pool sequences varying in length from 120 to 180 ft. Each segment began and ended at the top of a riffle, and the origin and end were permanently staked with PVC pipe and rebar. These two points served as reference to partially describe the channel geomorphology. A 300-ft measuring tape was secured between the origin pin and the end pin. Beginning at 0 ft (the origin pin), the orthogonal distance from the tape to the left bank, thalweg, and right bank was measured every 6 ft on the 300-ft tape. The data were used to develop overall channel configuration (planview) and to determine sinuosity of channel segments. Data derived from this work included meander wavelength, arc length, belt width, and the radius of curvature.

Table 1. Design criteria* for the restored Tulula Creek.

Parameter	Proposed Average Value	Range
Cross-sectional area	18 ft^2	15 – 20 ft^2
Bankfull Width	8.5 ft	8 – 10 ft
Average Depth	2.2 ft	1.6 – 2.9 ft
Maximum Depth	3.6 ft	2.2 – 5.3 ft
Width/Depth Ratio	4	3.1 – 6.3
Meander Wavelength	70 – 80 ft	60 – 100 ft
Sinuosity	1.62	1.44-1.93
Arc Length	50 ft	40 – 70 ft
Radius of Curvature	15 ft	10 – 25 ft
Channel Slope	0.0020	0.0017-0.0022
Rosgen Stream Type**	E5	

*North Carolina Department of Transportation (1997)
**Rosgen (1996)

In each of the eight segments, two riffles and two pools (defined as the middle of a meander) were chosen to establish permanent cross-sections. Bankfull width was determined and channel cross-sections were determined by taking depth measurements every 8 inches along a tape that was stretched from the two bank pins of a riffle or pool at the top of each bank. Bank inclination was determined with a clinometer. The cross-section data were used to calculate cross-sectional area, average depth, maximum depth, and the width/depth ratio. Erosion bank pins were installed at the toe or middle of a channel bank at a few riffle and pool cross-sections. The erosion pins were hammered 21 inches into the bank walls with 3 inches exposed in the channel. Pebble counts, using a modified Wolman method (Rosgen 1996), were conducted for each of the stream segments, when practical. Pebble counts were used to determine the particle size distribution of channel materials.

The slope of the water surface was surveyed using standard surveying equipment. A 300-ft tape was placed in the channel along the thalweg, with a start point in the channel by the origin pin. The features of each segment (each pool and riffle) were surveyed at the top of the left and right banks and for the thalweg. The water depth was also noted for the thalweg. The top, middle, and bottom of each riffle were surveyed as well as the middle of a meander. The distance of these features were noted from the 300-ft tape lying in the thalweg of the channel. The permanent riffle or pool cross-section pins were also surveyed. Benchmarks for each segment were chosen by using established NCDOT surveying points or by placing a nail in a nearby tree (benchmarks were established throughout the Tulula floodplain by NCDOT during channel construction). Overall slope of the water surface was calculated by dividing the difference in water surface elevation from the origin to the end of the segment (both points representing the top of a riffle) by the total stream distance.

The planview was evaluated before water release and after one year of water flow. The methods used to determine the planview (Moorhead et al. 2001a) are destructive of floodplain vegetation and annual evaluations were not warranted. The other geomorphic characteristics were evaluated before water release and annually for four years after water release into the restored channel.

Results and Discussion

The restored channel was constructed as five separate sections (Fig. 1). Eight random channel segments were chosen in the five sections (Fig. 2) to evaluate stream geomorphology over time. Water release began in Section 1 of the restored channel in September 2001. We placed two segments for channel evaluation in Section 1, one each in Sections 2 and 3, two in Section 4, and one each in Sections 5 and 5a. The initial bankfull width and changes in the cross-sectional areas of riffles and pools of the channel segments are listed in Table 1. There was essentially no change in the bankfull widths for 30 of the 32 permanent cross sections after four years of water flow and therefore, only the initial bankfull widths are reported in Table 1.

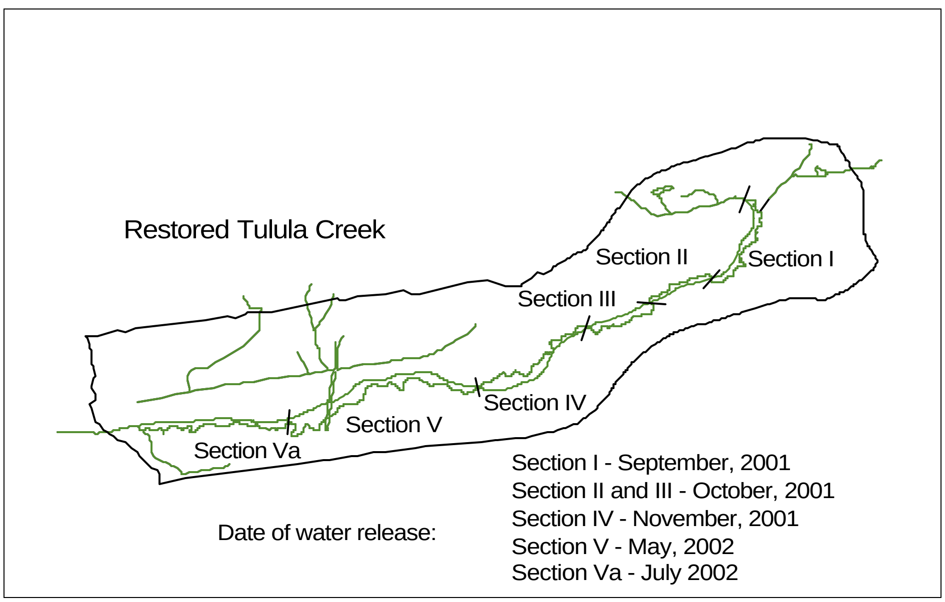

Fig. 1. Restored channel sections of Tulula Creek.

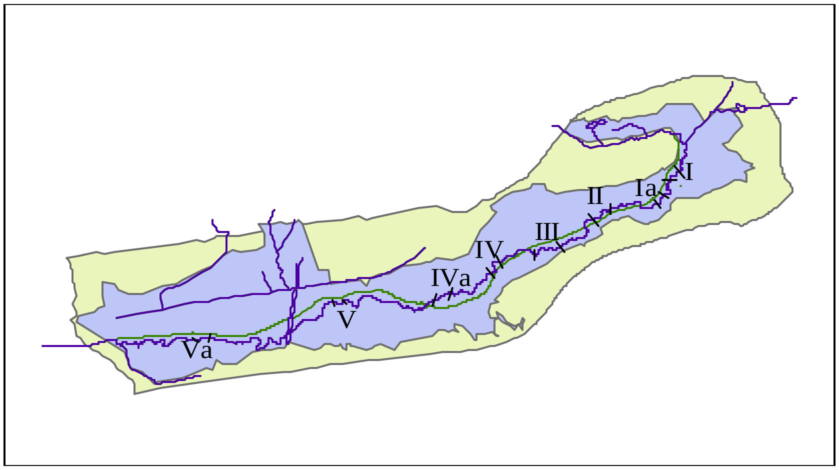

Fig. 2. Approximate locations of stream segments used for channel evaluations.

As anticipated, riffles typically had shorter bankfull widths compared to pools (Table 2). Bankfull width changed for one riffle and one pool in the area impacted by beaver dams. Beaver dams created bank stability issues for the constructed channel above and below the dam. Scouring of channel banks and substantial increases in cross-sectional area were noted five to ten linear feet above beaver dams. At one or more points above the dam, the water entered the floodplain and created fairly concentrated flow across lower lying areas of the floodplain. Eventually the water reentered the channel downstream and caused even more significant bank erosion. The constant flow of water over channel banks from beaver activity (where water entered the floodplain above the dam or reentered the channel below the dam) represented the most significant bank stability issues for the restored channel at Tulula. These stability issues were isolated at specific points along the restored channel at the lower end of the site.

Although bankfull width did not essentially change after four years of water flow, changes in cross-sectional areas were noted for both riffles and pools across the entire site (Table 2). A visual representation of riffle and pool cross sections is shown in Appendix A. Thirteen of 14 riffles increase in cross-sectional area after four years of water flow (Table 3). Six of those riffles had an increase of cross-sectional area greater than ten percent, two others were slightly less than ten percent. We designated ten percent as a numerical value of change that may represent a significant change in cross-sectional area, and hence may indicate areas of concern relative to channel stability. Most changes in cross-sectional area in riffles were due to scouring and deepening of the channel bed. Eight pools increased in cross-sectional area due to bed scouring. Six other pools decreased in cross-sectional area, typically at locations where point bars were forming. Six of the pools had a change in cross-sectional area greater than ten percent (three decreasing and three increasing) but there was no consistent pattern of change. The cross section of a stream changes much more rapidly and frequently in meander bends and, therefore, there is more variability in pool cross sections than in riffle cross sections (FISRWG, 1998). Changes in cross-sectional area are often used as an indicator of stream channel stability.

Increases in cross-sectional area represent areas of stream degradation (sediment erosion) while increases indicate aggradation (sediment deposition) of a stream channel. For Tulula, changes in cross-sectional area did not follow a consistent pattern. A few riffles and pools have degraded every year; others have alternated from aggradation and degradation of the channel bed. This probably represents adjustments of a constructed channel to various flow regimes over the past four years.

Table 2. Bankfull width (ft) and cross-sectional area (ft^2) and of riffles and pools in eight stream segments.

	Bank Full	--------------Cross-Sectional Area---------------		
	Width	Initial	Two Years	Four Years
Segment I				
Riffle 1	13.58	20.10	21.93	19.86
Pool 1	15.42	33.27	24.21	21.24
Riffle 2	11.81	14.59	15.69	15.58
Pool 2	15.42	26.71	28.92	25.89
Segment IA				
Riffle 1	10.50	13.84	16.36	15.86
Pool 1	10.27	19.07	19.76	19.58
Riffle 2	12.96	19.50	22.12	22.21
Pool 2	12.57	18.94	18.40	19.52
Segment II				
Riffle 1	16.34	19.67	21.93	21.49
Pool 1	16.01	30.26	27.80	23.89
Riffle 2	12.80	13.69	16.36	16.66
Pool 2	14.31	20.29	24.7	23.31
Segment III				
Riffle 1	13.29	18.55	20.06	22.42
Pool 1	18.87	31.27	32.99	28.91
Riffle 2	16.90	23.89	24.70	24.70
Pool 2	17.88	26.88	22.49	19.67
Segment IV				
Riffle 1	12.53	16.14	17.50	17.65
Pool 1	14.08	21.35	23.33	22.96
Riffle 2	12.73	18.91	22.57	21.26
Pool 2	14.57	26.38	27.59	26.51
Segment IVa				
Riffle 1	12.40	12.22	15.39	14.63
Pool 1	13.58	22.29	21.15	22.10
Riffle 2	15.13	19.22	21.50	20.38
Pool 1	13.52	19.71	21.74	23.13

Segment V				
Riffle 1	14.76	17.13	19.58	17.24
Pool 1	16.24	24.08	24.72	27.99
Riffle 2	13.78	15.45	16.66	16.61
Pool 2	16.33	28.32	33.33	33.38
Segment Va				
Riffle 1	9.68	15.24	16.98	beaver
Pool 1	11.65	18.14	19.60	beaver
Riffle 2	15.26	18.57	19.43	beaver
Pool 2	10.04	16.68	18.12	beaver
Average				
Riffle 1	12.89	16.61	18.72	18.45
Pool 1	14.53	24.97	24.20	23.81
Riffle 2	13.91	17.98	19.88	19.63
Pool 2	14.31	22.99	24.41	24.49

Table 3. Percent change in cross-sectional area of riffles and pools after four years of water flow. Numbers in brackets represent a decrease in cross-sectional area.

Segment	Riffle 1	Pool 1	Riffle 2	Pool 2
I	(1.2)	(36.0)	6.8	(3.1)
Ia	14.6	2.7	13.9	3.1
II	9.2	(21.1)	21.7	14.8
III	20.9	(7.5)	3.4	(26.8)
IV	9.3	7.6	12.4	<1.0
IVa	19.7	(1.0)	6.0	17.4
V	<1.0	16.3	7.5	17.9
Average	10.4	(5.6)	10.2	3.4

The average sinuosity of the restored channel was 1.32 (Table 4), compared to the design sinuosity of 1.62. The overall pattern of the restored channel did not change during four years of water flow. The slope of the water surface varies for the stream segments and has decreased over four years in most of the stream segments (Table 4).

The initial width/depth (W/D) ratio of riffles was slightly higher than for pools but after four years of flow the W/D ratio was similar for riffles and pools across the site (Table 5). A decrease in W/D in riffles was a result of slightly higher average and maximum depths of the channel with no increase in bankfull width. A W/D ratio of 12 is a high end value for “E” stream types (Rosgen 1996). The W/D ratio is used to understand the distribution of energy within a channel. If the W/D ratio increases, the hydraulic stress against the banks also increases and bank erosion is accelerated (Rosgen 1996).

Table 4. Sinuosity and slope of the water surface over time.

Segment	Sinuosity	Initial slope	At 1 year	At 4 years
I	1.23	0.0030	0.0036	0.0034
Ia	1.22	0.0024	0.0010	----
II	1.26	0.0022	0.0019	0.0008
III	1.43	0.0028	0.0026	0.0012
IV	1.29	0.0044	0.0047	0.0059
IVa	1.22	0.0022	0.0025	beaver
V	1.32	0.0024	0.0014	0.0004
Va	1.58	---	---	beaver
Average	1.32	0.0028	0.0025	0.0023

Table 5. Width/depth (W/D) ratio and maximum depth (ft) of riffles and pools (represents the average of seven stream segments).

Time	Riffle 1	Pool 1	Riffle 2	Pool 2	
Initial W/D	11.4		9.2	11.3	10.0
Two Years W/D	10.0		9.6	10.2	9.5
Four Years W/D	10.4		10.3	10.3	10.1
Initial max depth	2.06		2.97	2.21	2.72
Two years	2.74		3.07	2.88	3.24
Four years	2.79		3.05	2.91	3.25

Other physical characteristics of the stream segments suggest that the restored channel was not as sinuous as designed. This was reflected in the higher meander wavelengths and radius of curvature and lower belt widths of channel segments (Table 6) as compared with design criteria (Table 1). However, channel configuration has not changed after four years of water flow, suggesting that the geometry of the restored channel was suitable for the various flow conditions that occur in Tulula Creek.

Table 6. Other physical characteristics of selected meanders in each stream segment.

Section	Meander Wavelength (ft)	Arc Length (ft)	Belt Width (ft)	Radius of Curvature (ft)
I	65.6	45.3	42.7	19.4
Ia	68.9	24.3	43.6	10.2
II	95.1	55.8	55.8	23.3
III	98.4	66.3	57.4	21.0
IV	137.8	61.4	77.1	21.3
IVa	75.5	42.7	22.9	24.3
V	75.5	59.1	57.1	22.3
Average	88.3	50.5	50.9	20.3

The cumulative pebble counts of six stream segments are shown in Fig. 3. With the exception of stream segment V, 30 to 50% of the cumulative pebble counts were found in the silt/clay fraction after four years of water flow. Over time, sand particles have been replacing silt and clay particles as a dominate substrate in the Tulula channel. For example, after two years of water flow, the cumulative pebble counts of the stream segments were 40 to 70% silt and clay. Segment V has been covered with flood waters from a beaver dam for the past two years. After draining the area, we found the vast majority of the cumulative pebble counts to be in the silt/clay fraction. Before the beaver dam was established, the pebble count of this segment was about 45 % silt/clay. We would assume the same type of dominance of silt and clay particles for stream segments IVa and Va, both areas flooded by beaver dams.

Bank inclinations of riffles and pools created for the restored channel were commonly between 20 and 30 degrees (data not shown). Although significant erosion was noted at the bottom of the banks (toe of the bank slope) of riffles and pools (Table 7), overall bank inclinations did not change appreciably after four years of water flow because of the lack of erosion in the middle and upper portions of stream banks. The erosion noted at the bottom of channel banks through erosion control pins can be used to evaluate the lateral stability of a channel. Several points along the re-constructed Tulula channel are at risk of instability based on lateral erosion, most notably the riffle/pool sequence of Section Ia. The meander width ratio (meander belt width divided by bankfull channel width) is another indicator of lateral stability. Given the lack of changes in meander belt or bankfull width after four years of water flow, the ratio has not changed, suggesting that the re-constructed channel is fairly stable.

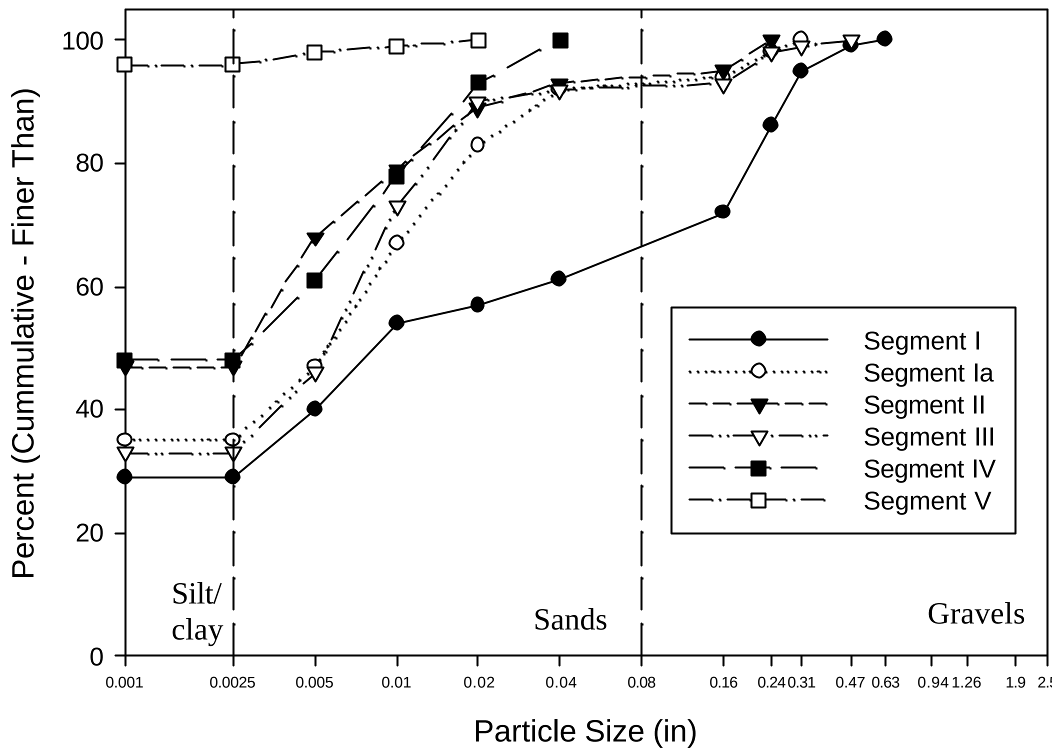

Fig. 3. Cumulative pebble counts of six stream segments after four years of water flow.

Table 7. Erosion of channel banks after four years of water flow, based on erosion control pins.

Segment	Feature	Location	Erosion (inches)
I	Pool 1	Toe	3.15
I	Riffle 2 Toe		3.15
I	Pool 2	Toe	7.48
Ia	Riffle 1 Toe		10.83
Ia	Pool 1	Toe	15.16
Ia	Riffle 2 Toe		3.74
Ia	Pool 2	Toe	13.78
II	Pool 1	Toe	3.07
II	Riffle 2 Toe		1.97
III	Riffle 1 Toe		1.57
III	Riffle 2 Toe		3.54
IV	Riffle 2 Toe		1.58
IV	Pool 1	Toe	5.91
IV	Pool 1	Middle	1.97

The overall channel configuration has not changed substantially after four years of water flow. However, changes in channel depth have altered the cross-sectional areas of riffles and pools. Desirable features have formed in the channel, most notably point bars on inside banks of many meanders. Changes in cross section and bank erosion at certain locations suggest that the channel is still adjusting to the flow regimes of Tulula Creek.

2. Hydrology

Concurrent with construction of the new channel, drainage ditches were blocked and filled. The expectation was that re-constructing a meandering channel would decrease water velocity, which, when coupled with blocked drainage ditches, would raise the level of the water table across the floodplain and allow for more frequent overbank flooding. One of our objectives was to determine if site restoration improved the overall site hydrology. Electronic water table wells were installed in July 2000 along transects that were perpendicular to the new channel (Fig. 4). In addition, site hydrology has been monitored for over twelve years with a series of manual water table wells and piezometers (Fig. 5). Many of the manual wells and all of the piezometers are located in a 4-ha floodplain/fen complex that serves as a reference area for several UNCA research projects. We have documented seasonal patterns of water-table elevation and vertical hydraulic gradient in this area and determined the influence of hillslopes and drought on fen hydrology (Moorhead 2001, Moorhead 2003).

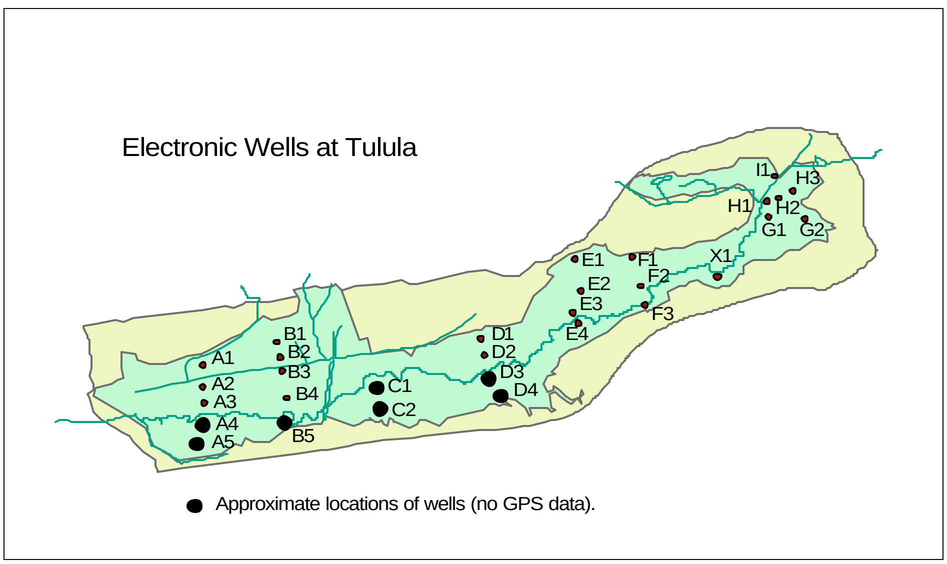

Fig 4. Transects and individual electronic wells used to assess site hydrology of the restored stream channel.

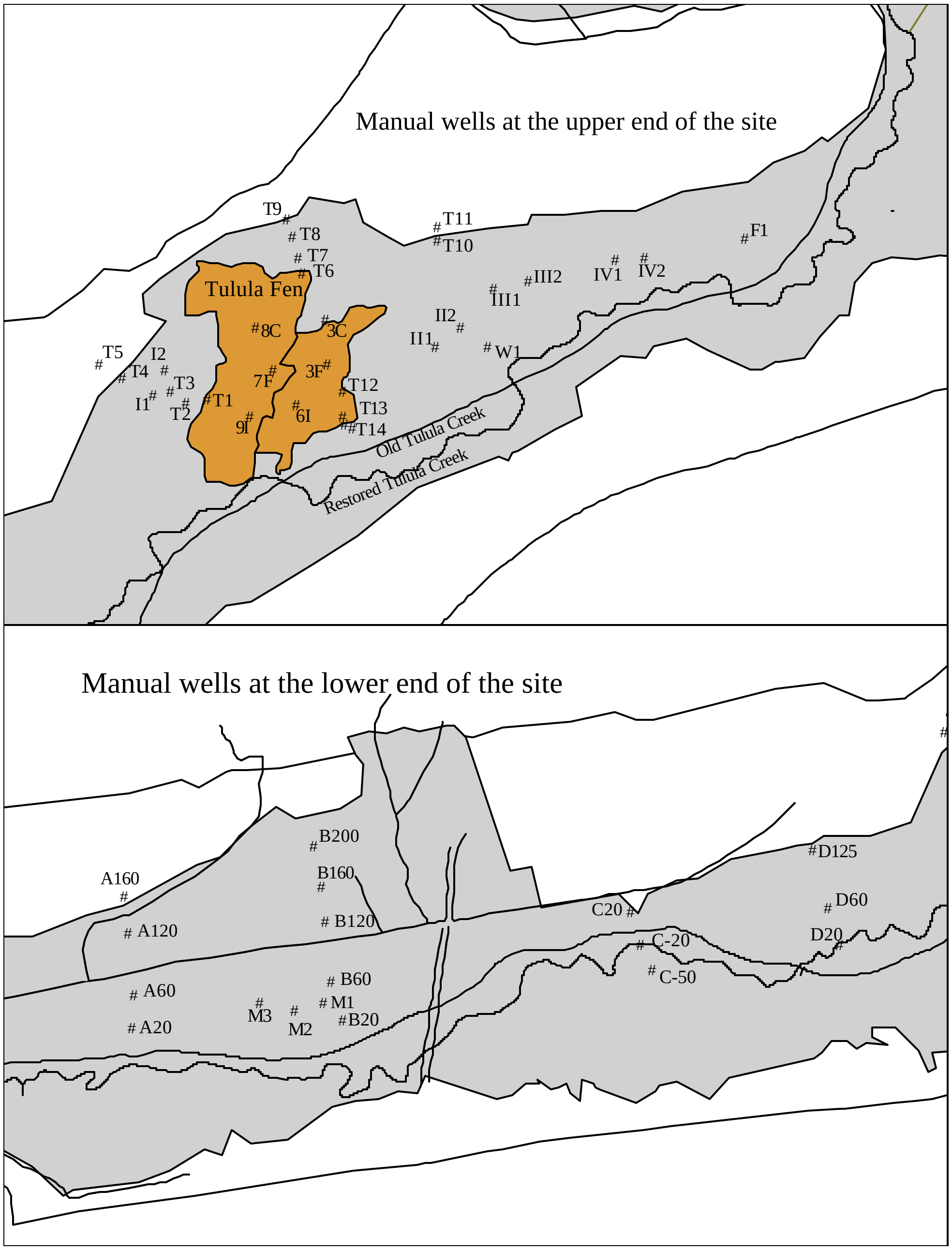

Fig. 5. Location of manual wells at Tulula. Wells A160, A120, B200, B160, B120, and D20 were destroyed during site restoration and were not replaced.

Methods

Both electronic and manual water-table wells were used to determine if the floodplain water table was higher because of the restored channel and blocked drainage ditches. Methods of installation are described in Moorhead et al. (2001a). The manual wells were read two to four times a month. The electronic wells were programmed to record the water-table depth on a daily basis. The data for both types of wells were converted to monthly averages to compare the pre- and post-restoration conditions. The monthly data were then used to construct hydrographs over a one-year period that coincided with the release of water in the various stream sections. For example, the months of September through the following August were used for developing hydrographs for electronic or manual wells in stream section I (water release in September 11, 2001). The pre- and post-restoration monthly averages provided an easier visual interpretation of changes in water table depth due to restoration. The monthly averages of water-table depths of 28 electronic wells are found in Appendix B. The monthly averages of water-table depths of 38 manual wells are found in Appendix C. Differences between the average monthly pre- and post-restoration water-table levels were analyzed with a Student's t-test in Microsoft Excel.

Results and Discussion

The success of hydrology restoration at Tulula, like many wetland sites, was determined primarily by changes in water-table depth. The assumption was that after the channel was restored and the drainage ditches were plugged, the overall water table of the site would rise. The electronic wells were also used by NCDOT to determine the success of wetland hydrology as determined by the Section 404 permitting system of the U.S. Army Corps of Engineers (at least 21 consecutive days of inundation or saturation during the growing season; North Carolina Department of Transportation, 2003).

The manual wells were installed during summer 1994 and provided seven to eight years of pre-restoration data (depending on the date of water release into various restored stream sections) compared with four years of post-restoration data. The electronic wells were installed in 2000, which gave one to two years of pre-restoration hydrology data compared with four years of post-restoration data. Using both types of wells provided a more thorough understanding of site hydrology and suggested a variety of trends for the site. The water table rose in some areas of the site (improved site hydrology), had no appreciable change in other areas, or in the case of one area of the Tulula floodplain, the water table dropped after site restoration (see Table 8).

The analysis was complicated by the presence of beaver at the lower half of the site. Beaver initially built a dam at the lower end of the site in 1999. They were trapped and theoretically removed, but they built more dams in 2000 and have had a presence at the lower end ever since. Several of the manual (A20, B20, C20, C50) and electronic wells (A3, A4, B4, B5, C1, C2, D3) showed the impact of beaver on site hydrology, with a typical hydrologic signature of a high-water table that remained essentially unchanged throughout the year. The net impact of beaver dams was to raise the water table and to create conditions of fairly permanent overbank flooding, but it also made it impossible to evaluate the impacts of stream restoration on site hydrology at the lower end of the site.

Table 8. Summary of water table changes at Tulula.

Wells	Higher Water Table	No Change	Lower Water Table
	Changes due to Stream Restoration		
Manual Upper End	F1, 6I, 9I, T12, T13, T14	3C, 3F, 8C, 7F, II1, II2, III1, III3, IV1, IV2, T9, T8, T7, T6, T10	T1, T2, T3, T4, T5 T11, I1, I2, D125
Manual Lower End		A60, M2	B60, M3
Electronic Upper End	I1, H1, H3, G1, G2, X1 E1, E2, E3, F1, F2 D1, D2		
Electronic Lower End	A5, B1, B2, B3		A1
	Changes due to Beaver		
Manual Lower End	A20, B20, C20, C50 D60		
Electronic Lower End	D3, C1, C2, A3, A4 B4, B5		
	Unclear		
Electronic	A2, H2		

Stream restoration did improve the hydrology of manual and electronic wells of the upper end of the site, if they were located within 75 ft of the channel. Manual wells located further from the stream showed little improvement in water table depth. Many electronic wells showed improvements in site hydrology regardless of location. The improved site hydrology at the upper end of the site based on data from electronic wells illustrates the difficulties of documenting restoration success with one year of pre-restoration hydrology data. It also suggested that the manual wells probably more accurately reflect the actual changes in site hydrology based on the seven years of pre-restoration data.

The large cluster of manual wells near and in Tulula Fen provided a more detailed analysis of changes in site hydrology. The cluster includes six wells in Tulula Fen, 14 wells located on four transects radiating into the Tulula Fen from adjacent hillslopes and the Tulula floodplain, and several additional wells located on the floodplain surrounding the fen. Two of the fen wells (9I, 6I) showed improvement in hydrology; both wells were closer to the restored channel relative to the four fen wells (8C, 3C, 3F, 7F) that showed no improvement in hydrology (Appendix C1a). The water table of wells on the Transect west of the fen (T1-T5) and on the floodplain (I1, I2) was lower after site restoration. However, the water table of wells on two transects north of the fen (T6-T9 and T10-T11) showed no improvement in water-table depth. The other transect runs between Tulula Fen and the restored channel (south of the fen) and the wells on this transect (T12, T13, T14) showed improved hydrology due to the close proximity of the restored channel.

Many of the electronic wells showed improved hydrology after site restoration, regardless of distance from the restored channel. Having one year of pre-restoration data for the electronic wells limited our ability to demonstrate the impacts of restoration on water-table dynamics. Annual variations in precipitation also contributed to perceived improvements of hydrology after restoration. In the 12 months before water release into Section I, 49.6 in of precipitation were recorded at Tulula, in the 12 months after water release into Section I, 61.8 in of precipitation were recorded. Determining the success of restoration based on hydrology was clearly complicated by the lack of pre-restoration data of the electronic wells, coupled with the increase in precipitation after restoration. The electronic wells continue to serve a useful function of documenting wetland hydrology for regulatory issues, but their limited utility for documenting overall changes in hydrology at Tulula should be noted.

The key to interpretation of changes in hydrology of Tulula was the long-term pre-restoration data associated with the manual wells. Data from some of the manual wells have been collected since 1994. Monthly averages of water-table depth were calculated for seven years of pre-restoration data and four years of post-restoration data (see Appendix C). The seven years of pre-restoration data included three years of drought conditions (July 1998 through fall 2001; Moorhead 2003) and several years of above-average precipitation. The average annual precipitation for the seven years before restoration was 59 in, the 30-year long-term average is 60 in. The average precipitation for the four years since restoration was 57 in. The data from manual wells provided a more comprehensive view of site hydrology and provided a better means of documenting actual changes in site hydrology due to restoration.

A composite map showing improvements in site hydrology due to stream restoration or beaver activity is shown in Fig. 6. Although improvements in site hydrology from stream restoration were restricted to a fairly narrow band of floodplain areas adjacent to the channel, many other areas of the Tulula floodplain were wetlands before site restoration. Beaver dams have created the wettest areas on the Tulula floodplain and their activity will probably expand upstream overtime, creating addition overbank flooding in the upper end of the site.

The main concern of NCDOT will be whether the wetlands of the Tulula floodplain have the appropriate hydrology to meet permit conditions. The data required for this determination are collected with the electronic wells and analyzed on a yearly basis (see North Carolina Department of Transportation, 2003 for examples). A more interesting ecological question is how the overall hydrology has changed at Tulula with site restoration. The manual wells provided the most valuable information for this question because of the seven years of pre-restoration data. This suggested that documenting changes in site hydrology requires a longer term effort of collecting water-table data. We recommend at least five years of pre-restoration data for hydrology, if average climatic conditions are noted through that period of time.

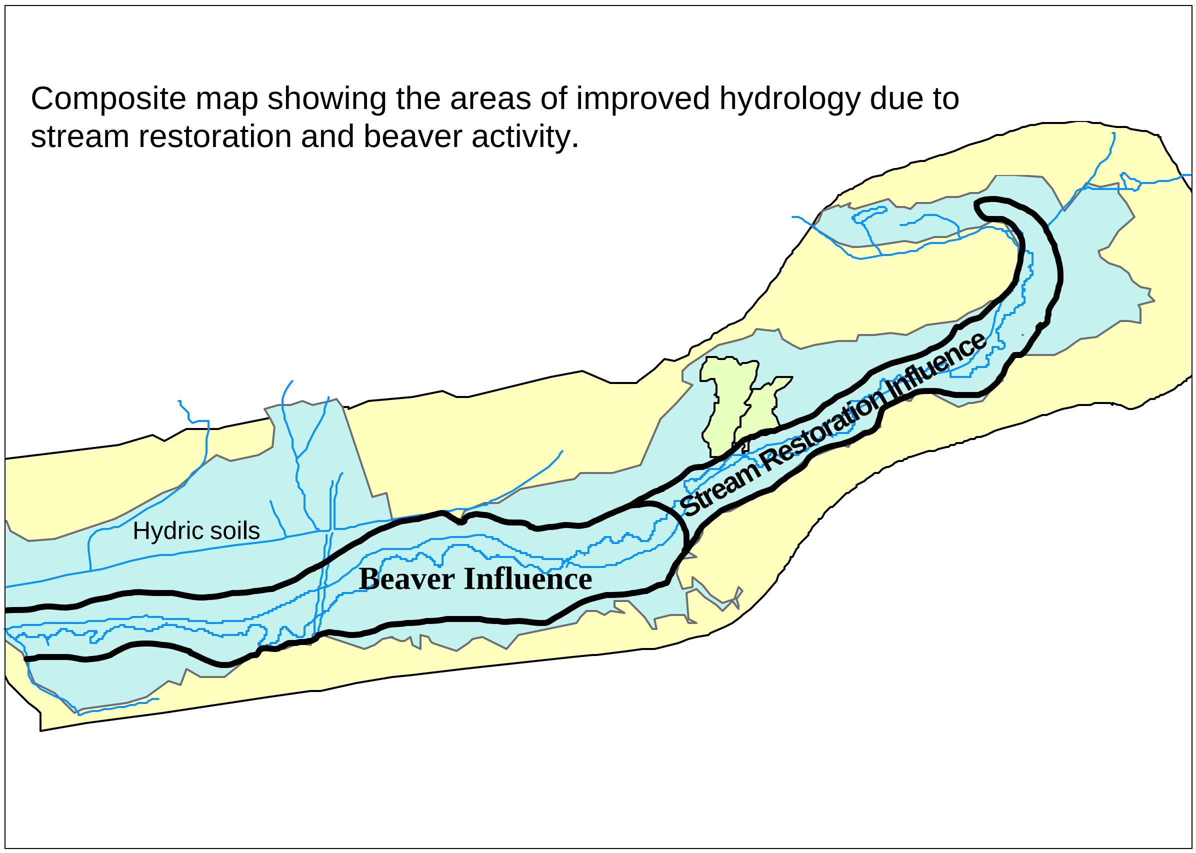

Fig. 6. Areas influenced by beaver dams or by stream channel restoration at Tulula.

B. Vegetation responses to restoration

1. Shrub responses to restoration and hydrologic regime

Since the Tulula floodplain was disturbed in the late 1980's, shrubs have become increasingly dominant in several formerly open parts of the floodplain, such as areas that were cleared for golf fairways, and along the banks of the restored creek. Shrubs are an important ecological stage in natural succession, as they provide more complex vertical structure than herbaceous plants, and many species provide fruits that are consumed by wildlife. Tag alder (*Alnus serrulata* (Ait.)Willd.) is a common shrub at Tulula, and is of particular ecological importance to wetland managers because of its status as a nitrogen-fixer. In order to better understand the dynamics of tag alder at Tulula, we examined alders in two recently restored areas of the floodplain (one in a depression with a high water table, and one on a low ridge with a lower water table). Both areas contained alders that were approximately five years of age. We also collected data in an unrestored area of the floodplain where the alders were approximately fifteen years old. Our objectives were to determine the impacts of hydrologic regime and disturbance (from restoration) on the growth and performance of tag alder. Variables that we examined included population density, plant size, reproductive status, annual stem growth, leaf size and biomass, and nutrient content of stems and leaves. We also examined infestation of tag alder by several insect herbivores: the phloem-feeding woolly alder aphid (*Prociphilus tessellatus*), and xylem-feeding spittlebugs (order Homoptera).

Methods

In 2004, we selected three areas at Tulula that had been disturbed during golf course construction in the mid 1980's. Two of the areas (restored wet and restored dry), had been restored in 2000 (Moorhead et al. 2001a), and currently support a large population of young alders. The third area, which was not restored, had been drained and graded for a golf fairway in the late 1980's, and has been undergoing natural succession since then. This area currently supports a small number of comparatively mature alders. The mean water table level in each area was measured by taking manual readings twice each month during 2004 from two water table wells in each area. Wells consisted of 39.4-in lengths of 1.4-in diameter PVC pipe with horizontal slits cut into the pipe at roughly 2-in intervals that had been installed to a depth 34 in.

In December 2004, we collected twigs and catkins from each area, for a preliminary analysis of plant nutrient content. We established one 65.6 ft x 82 ft plot in the restored wet area, and one 82 ft x 91.8 ft plot in the restored dry area (plot sizes differed due to the different dimensions of the alder thickets in each area). Twenty alder plants were selected at random in each plot, and the height of each plant was measured with a metered range pole. Because the unrestored area contained only 18 alder plants, we included all of them in the study. Four twigs representing current annual growth and bearing staminate (male) catkins were harvested from each plant in each area. The number of catkins present on each twig was counted, and the longest annual growth segment on the twig was measured. The four twigs with attached catkins from each plant were placed together in a small paper bag and dried to constant weight in a forced-air oven at 122° F. Once dry, catkins were separated from twigs. Twigs were weighed, then ground in a Wiley mill to pass a 40-mesh screen. Five catkin samples from each area were randomly selected and ground to pass a 40-mesh screen. Samples were sent to the Colorado Plateau Stable Isotope Laboratory at Northern Arizona University, Flagstaff, AZ, for analysis of nitrogen and carbon. Soil samples were collected from near the base of five randomly selected plants in each of the three areas. Five soil cores (1 in wide x 5.9 in deep) were taken from near the base of each plant base. Composited samples were air-dried and triple-sieved to remove particles >0.08 in. A small portion of each sample was ground to a fine, homogeneous powder with a mortar and pestle and submitted to the Colorado Plateau Stable Isotope Laboratory for analysis of nitrogen and carbon.

Analyses of variance (ANOVAs) were performed for plant height, twig length, twig weight, number of catkins per twig, mean catkin weight, and the C and N content of twigs, catkins, and soils. The three areas (restored wet, restored dry, and unrestored) were used as classes. Differences among areas were interpreted using Tukey's multiple comparison procedure. An Analysis of Covariance (ANCOVA) was performed to control irrelevant variation in annual growth variables due to plant height (and by association, plant age).

In June 2005, we established plots of equal size (82 ft x 98.4 ft) in the densest part of the alder thickets in the restored wet and dry areas. All alder plants within each plot were tagged, and the basal diameter of all stems within each plant was measured. Stems that had a basal diameter of <0.4 in diameter at ground level (dgl) were considered "sprouts" (LeBlanc and Leopold 1992), and were counted for each plant, but their basal diameters were not measured. In July 2005, the reproductive status of each plant in the plots was noted by documenting the presence of pistillate cones. Leaf production was examined by randomly selecting 20 plants in each plot, and harvesting 20 random leaves from each plant. Leaves were kept on ice in coolers in the field, then refrigerated. The area of each leaf was measured using a CI-202 leaf area meter (CID, Inc., Vancouver, WA). Leaves were scanned twice, and the two readings were averaged. If the leaves were damaged by herbivory, two additional readings were taken after all holes were covered with small pieces of black construction paper. Leaves were dried in envelopes in a forced hot air oven at 122^{o} F, and weighed once they reached a constant weight. All 20 leaves from each plant were ground in a Wiley mill to pass a 40-mesh screen, and sent to the Colorado Plateau Stable Isotope Laboratory at Northern Arizona University (Flagstaff, AZ) for analysis of carbon and nitrogen. In August 2005, we surveyed plants for the presence of woolly alder aphids, which are found in clusters along the larger stems, and for spittlebugs masses, which occur along current growth. Due to time constraints, we only surveyed plants in the restored wet and dry areas. To better quantify the extent of the spittlebug infestation (which was extensive), we selected 15 plants at random in each area from all plants hosting spittlebugs, and counted all spittle masses on each of these plants (one juvenile spittlebug occupies each spittle mass). Because we counted masses and did not examine individual insects, it is unknown whether more than one species of spittlebug was present.

ANOVAs were performed for the mean number of stems and sprouts per plant, basal diameter, leaf weight and area, leaf carbon, leaf nitrogen, and the number of spittlebug masses per stem. The three areas (restored wet, restored dry, and unrestored) were used as classes, and differences among areas were interpreted using Tukey's multiple comparison procedure.

Results and Discussion

In 2004, the mean water table level (-19.3 in) was lowest in the unrestored area. This area had been drained and graded in the mid-1980s, and the recent restoration activities did not have much of an impact on the water table there. The water table was intermediate (–9.1 in) in the restored dry area, and highest (+3.3 in) in the restored wet area (Fig. 7). The restored wet area included a topographic depression that contained pools of standing water, as well as some flowing water.

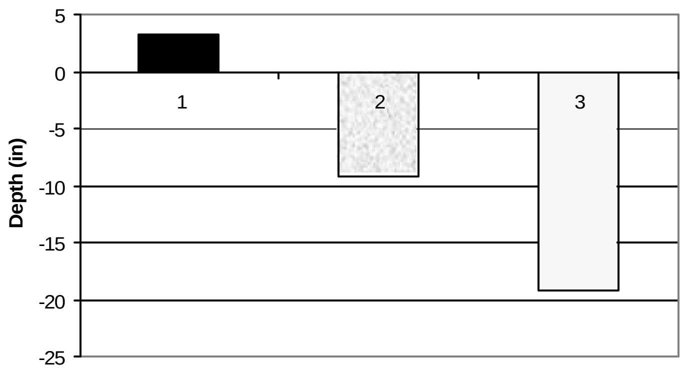

Fig. 7. Mean water table levels for (1) restored wet, (2) restored dry, and (3) unrestored areas of the Tulula floodplain in 2004.

The analysis revealed no significant impact of plant height on other measured annual growth variables. Plants in the unrestored area, which were at least 10 years older than those in the other areas, were significantly taller (15.4 ft) than plants in the restored dry (9.5 ft) and restored wet (7.9 ft) areas (P<0.001; Table 9). Twigs in the unrestored area were significantly shorter than those in the restored dry area (P = 0.002). Although the difference in twig length suggests differences in resource allocation, twig biomass did not differ significantly among the study areas (P=0.121). Longer twigs may have received more resources and energy during primary growth, while thicker twigs may have received more resources during secondary growth, resulting in similar biomass, but different lengths. Also, stem elongation can be a phenotypic response to light availability (Gurevitch et al. 2002), which may account for the variability we observed among our study areas. Neither the number (P=0.120) or weight (P=0.052) of staminate catkins differed among the three areas (Table 9). The P-value for catkin weight was nearly significant, indicating that a larger sample size might have shown that catkins in the restored dry area were lighter.

Table 9. Characteristics of current twigs and staminate catkins of tag alder in three different areas of the Tulula floodplain in December 2005. Values followed by the same letter are not significantly different (P>0.05), and can only be read within columns.

Site	Mean height (ft)	Mean twig length (in)	Mean twig weight (oz)	Mean no. catkins	Mean catkin weight (oz)
Restored Dry	9.5b	11.6a	$2x10^{-4}$a	1.6a	$2x10^{-6}$a
Restored Wet	7.9b	9.4ab	$2x10^{-4}$a	1.5a	$4x10^{-6}$a
Unrestored	15.4a	7.6b	$2x10^{-4}$a	1.2a	$4x10^{-6}$a

Soil carbon was significantly higher in the restored wet (10.0%) and unrestored (9.1%) areas, and lowest in the restored dry area (2.5 %; P = 0.001; Table 10). Soil nitrogen also differed significantly among the three areas (P < 0.001), with highest soil nitrogen (0.61%) occurring in the unrestored area, and the lowest soil nitrogen (0.13%) in the restored dry area. The higher soil nitrogen in the unrestored area likely reflects the longer time period that has elapsed since soils in that part of the floodplain were disturbed. The low carbon and nitrogen in the restored dry soil may be attributed to the fact that this area was situated on a slight microtopographic rise created during the wetland restoration, when the site was contoured by heavy equipment. Observation of soil characteristics such as color and texture suggest that the soil on this slight ridge originated in lower horizons of the profile, which are typically lower in carbon (Singer and Munns 2002).

Table 10. Carbon and nitrogen content of soils, twigs, and staminate catkins from three areas of the Tulula floodplain in December 2005. Values followed by the same letter are not significantly different (P>0.05), and can only be read across rows.

Characteristic	Restored wet	Restored dry	Unrestored
Soil carbon (%)	10.0a	2.5b	9.1a
Twig carbon (%)	52.8a	51.9a	53.3a
Catkin carbon (%)	57.4a	55.7a	57.4a
Soil nitrogen (%)	0.4b	0.1c	0.6a
Twig nitrogen (%)	1.1c	1.3b	1.5a
Catkin nitrogen (%)	2.1a	2.2a	2.1a

Twig nitrogen, which was highest in the unrestored area, and lowest in the restored wet area (P<0.001), declined as the water table increased. Twig nitrogen also appeared to be associated with time since disturbance, with higher nitrogen occurring in the unrestored area. Variation in twig nitrogen along both water and restoration gradients suggests differing levels of nitrogen fixation. It is known that actinomycete symbiosis in alders is affected by water table levels (Weber et al. 1989); hence, nitrogen fixation in the restored wet area may have been inhibited by the higher water table. The higher twig nitrogen in the unrestored area may also reflect the higher soil nitrogen in that area, although soil and twig nitrogen were not correlated in the two restored areas. Twig carbon (P = 0.100), catkin carbon (P= 0.293), and catkin nitrogen (P=0.801) did not differ significantly among the three areas. The similar nitrogen content, number, and biomass of catkins among the three areas may be attributed to the fact that we collected our samples during the winter, when physiological activity of alders was limited to catkin production.

We documented nearly twice as many alder plants in the restored wet area (308) as in the restored dry area (166; Table 11). Very few alder plants (18) occurred in the unrestored area. More than 40% of alder stems in the restored wet and dry areas were <1.2 in dgl, and the plants in both of these areas were small, with about the same number of stems per plant (between 5 and

6). We know that these plants did not exceed five years of age. In contrast, the plants in the unrestored area were ten years older, had more than twice as many stems (P<0.001) and more sprouts (P<0.001) per plant, and had stems that were more than twice as large in diameter (P<0.001). Reproduction in the older plants was also more prolific, with almost 90% bearing pistillate cones, compared with 57% of the plants in the restored wet area, and less than 20% in the restored dry area. Leaves in the unrestored area were twice as large (10.9 in^2) as those in either restored area (approx. 5.4 in^2). Leaves in all three areas had similar weights (P=0.171), nitrogen (P=0.908), and carbon (P=0.691) content.

Table 11. Characteristics of *Alnus serrulata* plants in three areas of the Tulula floodplain. Values followed by the same letter are not significantly different (P>0.05), and can only be read across rows.

Characteristic	Restored wet	Restored dry	Unrestored
Total number of plants	308	166	18
Mean number of stems per plant	5.5 b	5.8b	12.4a
Mean basal diameter of stems (in)	0.8c	0.9b	1.6a
Percent of plants with sprouts <0.4 in dgl	90.6	60.2	100.0
Mean number of sprouts <0.4 in dgl per plant	6.1b	2.2c	9.6a
Percent of plants with pistillate cones	56.5	17.5	88.9
Mean leaf weight (oz)	0.1a	0.1a	0.1a
Mean area per leaf (in^2)	5.3b	5.6b	10.9a
Percent of leaves exhibiting damage	43.5	59.4	60.8
Mean area of damage on leaves (in^2)	1.8a	0.3b	0.5b
Percent leaf carbon	49.0a	49.0a	48.8a
Percent leaf nitrogen	2.4a	2.4a	2.4a
Percent of plants with spittle masses	73.0	70.9	---
Mean number of spittle masses per stem	15.9a	11.1a	---
Percent of plants with woolly alder aphids	2.6	---	---

Alders in the restored wet area were similar in age to those in the restored dry area, yet the wet area contained almost twice as many plants, had nearly three times as many sprouts per plant, and three times as many plants produced pistillate cones. Given the trend noted earlier towards a lower weight of staminate catkins in the restored dry area (Table 9), the wet area was clearly more suitable to the establishment and reproduction (both sexual and asexual) of tag alder. However, the plants in the restored wet area had a smaller diameter and lighter leaves (in terms of biomass) than those in the restored dry area. These differences could have resulted from crowding and intraspecific competition. However, it is known that water table level can affect actinomycete symbiosis (Weber et al. 1989), which may have influenced biomass production (smaller basal diameter and lighter leaves) in the wet area. In the unrestored area, the taller, older plants, although fewer in number, were largest in basal diameter, had the most stems and sprouts per plant, and nearly 90% of plants produced pistillate cones. Although the number of staminate catkins produced on twigs in the winter did not vary among the three areas (Table 9), the production of pistillate cones during the spring and summer would have required a greater allocation of resources. Kaelke and Dawson (2003) reported that larger, older alders have greater carbohydrate reserves than younger plants do, which would allow them to divert more resources to reproduction, which was evident in our study (for both sexual and asexual reproduction). In addition, soils in the unrestored area contained more nitrogen (Table 10), which may have facilitated alder growth and reproduction. Although the unrestored plants produced the largest leaves, since the leaves were no heavier than those in the restored areas, the larger size may have been a response to self-shading within the canopy of these taller plants.

In terms of herbivory to alder leaves, the restored wet plants had the lowest percentage of leaves exhibiting damage (Table 11). However, damaged leaves from that area lost significantly more leaf area (1.8 in^2) than did damaged leaves in the restored dry (0.3 in^2) or the unrestored (0.5 in^2) areas ($P<0.001$). Clearly, herbivory was less extensive, but more intensive in the wet area. Differences in leaf nitrogen were not the reason, and we did not examine leaf-chewing insects to determine which might be contributing to this damage. We did, however, examine two types of sap-feeding insects. Woolly alder aphids are phloem-feeders that congregate along the stems of tag alders and feed by piercing the bark. Less than 3% of plants in the restored wet area were infested with woolly alder aphids, and we documented no alder aphids in the restored dry area. Although phloem-feeding insects remove carbohydrates from plants, the low level of aphid infestation that we documented in the wet area is unlikely to have had a significant impact on the alders. On the other hand, spittlebugs are xylem feeders that remove nitrogen along with xylem fluid, and actinorhizal nitrogen-fixing plants such as alders are known to be major hosts of spittlebugs (Thompson 1999). We found spittle masses concentrated on young alder tissues in both the wet and dry areas, primarily at the base of leaf petioles and reproductive structures. We documented spittle masses on nearly 75% of plants in both areas, and the distribution of spittle masses (16 per stem in the wet area, and 11 per stem in the dry area) did not differ significantly between the two areas ($P=0.606$).

Summary

Tag alder is found across the Tulula floodplain, so it is clearly suited to a wide range of ecological and hydrologic conditions, and its ability to fix nitrogen makes it an important part of the wetland community. Because tag alder is a long-lived woody species, time elapsed since disturbance has obvious implications for its growth and establishment (e.g., longer time since disturbance = older, larger plants with greater sexual and asexual reproductive success). Disturbance of the soil profile by earth-moving equipment during restoration at Tulula disrupted the soil profile, resulting in lower levels of soil carbon and nitrogen in the restored dry area. Alders in this area showed lower reproductive success, with fewer vegetative sprouts per plant, a trend towards lighter staminate catkins, and a smaller percentage of plants bearing pistillate cones. Wet soils appeared to favor the establishment of tag alder, with the densest growth occurring in the restored wet plots. However, the basal diameter of these plants was smaller than that of plants growing in less-crowded, drier soils. We noted herbivore damage on tag alder leaves in both wet and dry soils, with more damage to leaves occurring in wet soils. However, this difference was not correlated with levels of leaf carbon or nitrogen, which did not differ between our three study areas. Sap-feeding insect herbivores were noted in both wet and dry areas, with little difference noted in the levels of infestation.

2. Survival of commercial red maple stock

It is common practice for wetland managers to replant woody vegetation when wetlands are restored, in order to achieve a forested canopy as rapidly as possible. Our objective was to purchase and plant tree seedlings at Tulula, document their survival at this site, and determine whether large-scale planting was necessary or advisable. We selected red maple (*Acer rubrum* L.) as our focal species, as it is one of the most abundant species in the Tulula floodplain, ensuring that conditions are generally conducive to its growth.

Methods

During the winter of 1995, we planted 231 bareroot red maple seedlings, which were purchased from a nursery in central Tennessee. Seedlings were planted in three 65.6 ft x 98.4 ft plots (77 seedlings per plot) established in a former golf fairway. We inventoried the living maples, and measured their heights, during July 2005.

Results and Discussion

Survival of the planted maple seedlings has declined since the seedlings were set out in 1995. Survival was 71% in 1996 (one year after planting), 66% in 2003, and 47% in 2005 (the current study period). There are probably a number of reasons for this decline, but the most likely is the intense competition the seedlings face from aggressive plants such as blackberries (*Rubus argutus* Link) and vines (such as *Clematis virginiana* L.). Over the last ten years, these competitors have dominated parts of the former golf fairway where the maple seedlings were planted, to the point where some of the plots are impenetrable. The highest survival of planted maple seedlings has been in areas of the former fairway where the growth of grasses and herbaceous plants is sparse. In 2005, heights of the planted trees varied from 1.3 ft to 19.7 ft, with an average height of 6.2 ft. Despite the continued decline of the planted maple seedlings, naturally-regenerating red maples are flourishing in this fairway, as well as across the floodplain. Many of these germinated after our seedlings were planted, and many are taller and more vigorous than the planted stock. It is clear that natural succession will restore the original floodplain forest, without the need for intervention on our part. In fact, the seed source of the purchased seedlings is unknown, while the naturally-regenerating seedlings came from parent plants that are adapted to this site.

C. Effects of Restoration on Decomposition and Soil Microfauna

Decomposition is a primary ecosystem function in the recycling of nutrients (Swift et al., 1979; Seastedt,1984), and is influenced by factors such as soil nutrients, temperature, composition of plant material, and composition and activity of soil fauna (Coleman, 1985). Although many studies have been done on decomposition in upland hardwood communities in the southern Appalachians (see Reynolds et al., 2003), and some research has been done on decomposition in cypress-gum wetlands (Battle and Golliday, 2001) and playa wetlands in the southern Great Plains (Anderson and Smith, 2002), little has been published about decomposition in wetlands of the southern Appalachians except for recent work by Neher et al. (2003).

The vital role of microarthropods in decomposition and nutrient cycling has been long established (Swift et al., 1979; Coleman, 1985). Soil and litter microarthropods feed upon soil microbes, the primary decomposers, thus affecting microbe community structure. Microarthropods also may transport microbial propagules and thus help to disperse these decomposers and catalyze the rate of decay (Petersen and Luxton, 1982; Wardle, 2002; Coleman et al., 2004). In addition, microarthropods fragment litter and excrete nutrient rich frass (Petersen and Luxton, 1982; Coleman et al., 2004; Cole et al., 2006). Due to their importance in decomposition and distribution of soil organic matter, soil and litter microarthropods have been suggested as useful bioindicators of the effects of land management on nutrient dynamics (Bird et al., 2004).

Neher et al. (2003) compared decomposition of museum board (primarily cellulose) and balsa wood between disturbed and undisturbed areas and among agriculture, forest and wetland ecosystems in North Carolina. They found that decomposition of museum board in wetland soils was greater initially in disturbed than undisturbed sites, but later the regression lines for percentage of museum board substrates were parallel, suggesting similar magnitudes of decay. Balsa wood decomposition in all ecosystem types and both levels of disturbance was similar.

Our objectives for this study were to compare decomposition and microarthropod community structure among five plant communities, representing differing levels of disturbance, at the Tulula Wetlands Mitigation Bank, a mountain floodplain/fen complex, and relate these data to soil pH, moisture, and organic carbon. We have found no other published studies which focus on decomposition and microarthropods in a wetland.

1. Decomposition and Soil Properties

Methods

Six plots were established in each of five plant community types at Tulula. Plant communities used were red maple forest (RM), open (OF) and closed fen (CF), early successional floodplain (FP), and a former golf fairway – a disturbed alluvial bottomland (DA). The red maple forest (RM) is approximately 50 years old and grows in a floodplain approximately 1000 m downstream from the two fen, FP, and DA sites. The CF was logged about 34 years ago (Warren et al., 2004). The open fen (OF) and floodplain (FP) were cleared in the mid 1980s, and the floodplain bushhogged in 1994, as part of the development. Thus the five study sites not only present a variety of vegetation types, but represent a gradient in terms of age since disturbance. The fen sites receive a steady input of ground-water flow; the floodplain sites are drier (Rossell et al., 1999; Moorhead et al., 2001a). Red maple is the dominant canopy species in RM and CF, and is a dominant sapling in the OF and FP. The FP and DA were cleared for a golf course in the mid 1980's and the DA bulldozed back into a "floodplain" type area in late 1999, as a series of golf ponds were partially backfilled. Drier areas of the DA, where we sampled, are dominated by blackberry (*Rubus argutus* Link), groundnut (*Apios americana* Medik.), goldenrod (*Solidago* spp.), common rush (*Juncus effusus* L.) and witch grass (*Dicanthelium* spp.) (I. Rossell, personal communication).

Twelve fiber-glass screen litter bags, 15 X 15 cm with mesh size 1.5mm, containing known weights of air-dried red maple (*Acer rubrum*) leaves were placed in each plot in a 4 x 3 m grid. The fresh-fallen leaves were collected in October, 2002, and the litter bags placed in the field in January, 2003. Each litterbag was anchored with a survey flag and lightly covered with surrounding litter**.** One litterbag was removed from each plot every other month, beginning in March, 2003 and continuing through May of 2004. Individual litterbags were placed in zip-loc bags, all bags were then transported in a cooler to the lab, and the litter content weighed (dry weight) after microarthropod extraction. Percent mass remaining of litter was calculated.

Soil analyses were conducted on individual cores (5 cm deep, 4 cm diameter = volume of 62.83 cm^3) taken through the litter layer from each plot in May 2004 and April 2005. Percent organic carbon content was determined by the Walkley-Black method (Nelson and Sommers, 1982); pH was measured on a 1:1 slurry of soil:distilled water using a Fisher Accumet pH meter and a standard electrode**.** Average values of pH and organic carbon were calculated for each plant community, combining the two years.

Soil moisture measurements were made in the field with a Campbell Scientific Hydrosense (Campbell Scientific, Inc. Logan, Utah) beginning in May 2004 within each litterbag plot. Since August, 2004, triplicate measurements were taken in each plot and the values averaged for statistical analyses. Measurements from May 20, 2004, through April 16, 2005, the same period included in soil pH and organic carbon measurements, were used for Tukey's Studentized Range (HSD) test and for Spearman's Correlation test.

Tukey's Studentized Range (HSD) Test, (SAS version 9.1, 2005), was used for statistical analysis of percent litter mass remaining and soil characteristics. Proc Corr, with Spearman correlation coefficients, (SAS version 9.1, 2005) was used for correlation analysis among percent litter remaining, total number of microarthropods, soil pH, soil moisture, and soil organic carbon.

Results and Discussion

After two years in the field, decomposition in RM was significantly greater than the other sites, although there was no significant difference in decomposition among the other four sites (Fig. 8). The RM site is the least disturbed site at Tulula, and also has the highest percent soil organic carbon (OC; Fig. 9) and the lowest soil pH (Fig. 10).

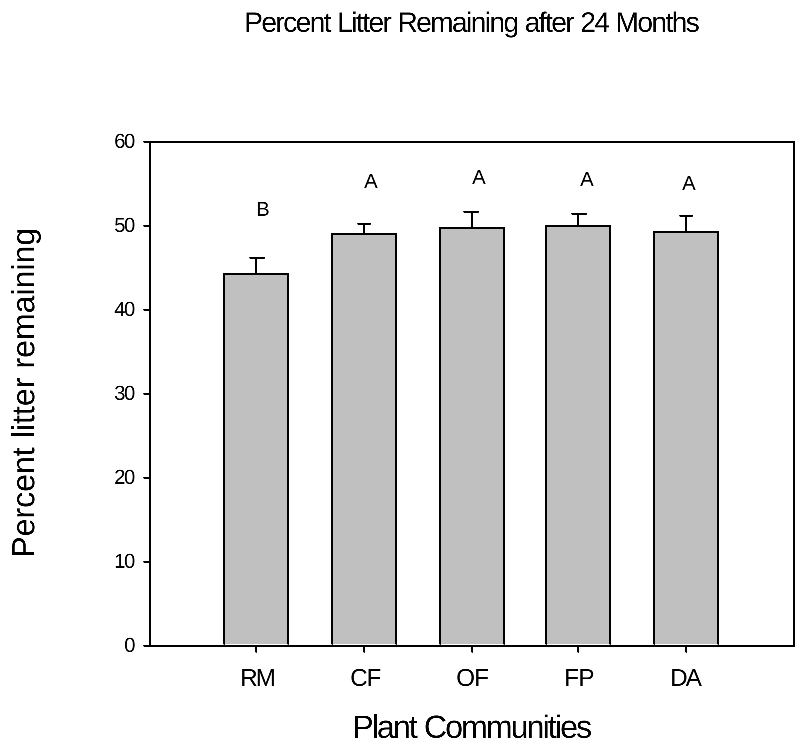

Fig. 8. Percent litter remaining in litterbags after 24 months in the field. Plant communities are RM=red maple, CF=closed fen, OF=open fen, FP=flood plain, and DA=disturbed alluvial bottomland forest. Each bar is the average of 52 to 72 litterbags. Bars with the same letter are not significantly different; error bars are ± 1 SE.

Average organic carbon varied from 30.26% to 4.17% (Fig. 2) and was highest in soils from RM (30.26%), with organic carbon decreasing in this order: CF (25.44%)>OF (20.24%)>FP (14.29%)>DA (4.17%). Organic carbon in the FP and DA was significantly lower than in RM and CF. The significantly lower OC for DA is probably the result of mixing soil horizons after bulldozing the area for a fairway and then back again to recreate floodplain. In addition, the DA site has had less addition of carbon from leaf litter compared to the RM. Sites with the least disturbance, and thus the more mature plant communities -the fens and red maple forest, have the highest OC in the soil. In addition, the OC data are probably strongly influenced by the amount of litter in the cores taken for soil analyses. Since soil organic matter is known to be strongly influenced by soil fauna (Coleman et al., 2004), these results appear to be correlated with the distribution of microarthropod abundances, especially for RM and OF (Fig. 9). Spearman's correlation coefficients substantiate this positive correlation, with a value of 0.60 for the relation between litter total microarthropods and soil organic carbon (Table 12).

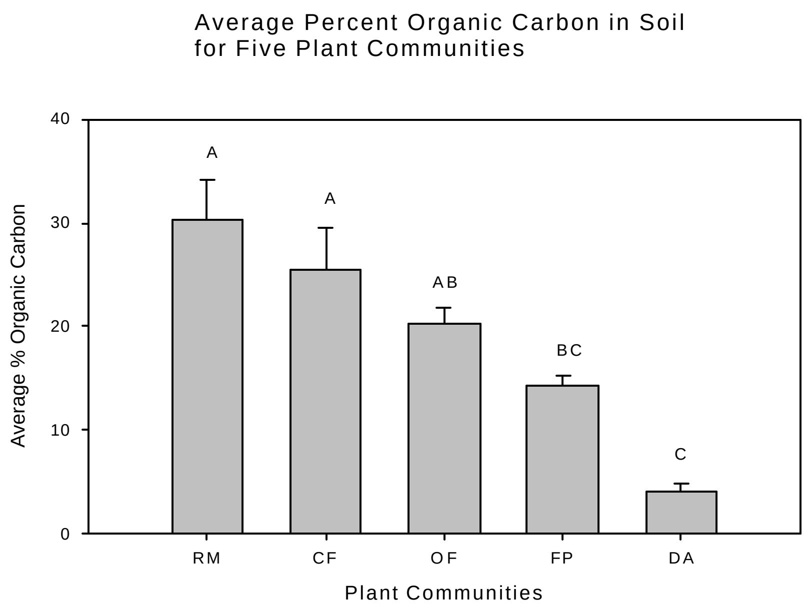

Figure 9. Average percent organic carbon for soil from five plant communities: RM=red maple, CF=closed fen, OF=open fen, FP=flood plain, DA=disturbed alluvial bottomland forest. Each bar is the average of 11-12 soil core samples. Bars with the same letter are not significantly different; error bars are ± 1 SE.

Average soil pH values ranged from 3.44 to 4.23 (Fig. 10), with the DA having the highest pH (4.23), followed by FP (4.02), OF (3.78), CF (3.70), and RM (3.44). pH was significantly lower for RM compared to all other sites.

Soil moisture was significantly lower for RM and DA (52.6% and 48.1%, respectively) than the other sites, which increased in the order FP (60.7%), CF (84.9%), and OF (95.4%). These last three sites were significantly different from RM and DA (which were not significantly different) and significantly different among themselves.

Although correlation analyses did not indicate any strong relation between percent litter remaining and pH or organic carbon (Table 12), we suspect an indirect relation, at least, because litter total microarthropods had a strong negative correlation with soil pH and a strong positive correlation with soil percent organic carbon. Spearman's Correlation procedure found no significant correlation between soil moisture and percent litter remaining, or between soil moisture and total microarthropods. Since no correlation was found between soil moisture and percent litter remaining or between soil moisture and total microarthropods, and the sites with highest (RM) and lowest (DA) decomposition had similar soil moisture, we conclude that soil moisture was adequate in all sites to support decomposition and microarthropod communities and that it did not contribute to differences we found among the sites.

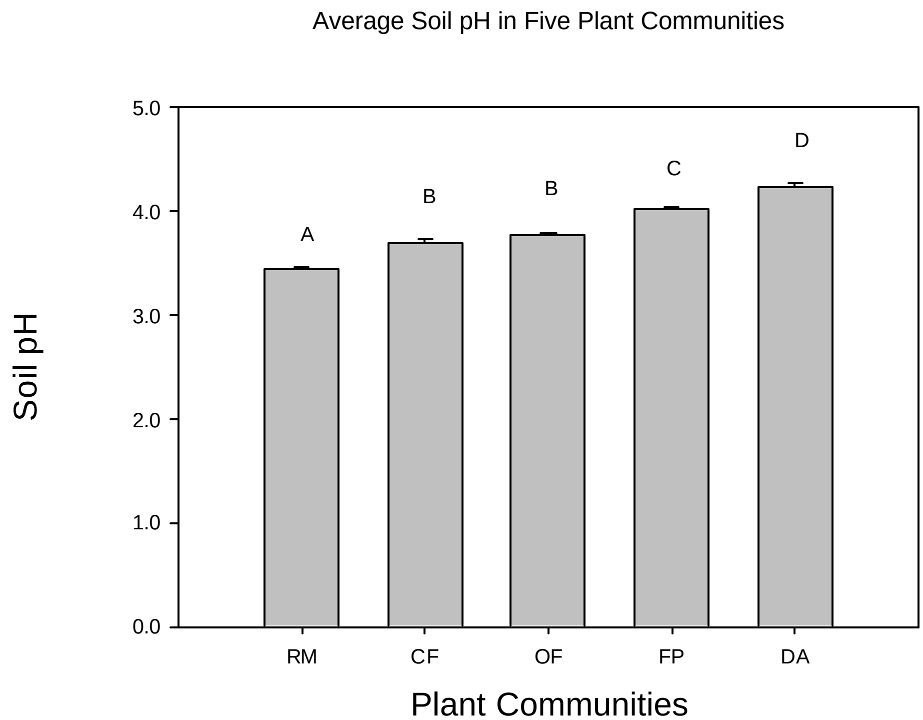

Fig. 10. Average pH for soil from five plant communities: RM=red maple, CF=closed fen, OF=open fen, FP=flood plain, and DA=disturbed alluvial bottomland forest. Each bar is the average of 11 to 12 soil core samples. Bars with the same letter are not significantly different; error bars are ± 1 SE.

Table 12. Spearman correlation coefficients for percent litter remaining and total microarthropods with soil pH and soil percent organic carbon. Data for percent litter remaining, pH, and organic carbon were from May 2004 and April 2005; data for total microarthropods were from May 2004. Number of observations is in parentheses.

	Percent litter remaining	*Total microarthropods*
pH	0.001 (49)	-0.634 (26)
organic carbon	0.009 (48)	0.603 (25)

It is widely accepted that soil microarthropods play an important, though often indirect, role in decomposition (Coleman, 1985; Swift et al., 1979; Wardle, 2002). Neher et al. (2003) did find a negative correlation between soil pH and percent of substrate remaining (museum board and balsa wood in their study) but no correlation between percent substrate remaining and percent soil organic matter (SOM). In comparing disturbed and undisturbed wetland sites for decomposition, Neher et al. (2003) found similar magnitudes of decay for museum board after the initial incubation period. This contrasts with our data which indicate greater rates of decay in our least disturbed wetland area compared to more disturbed sites. However, the pH of our RM, the least disturbed site, was much lower than the Neher et al. study (RM=3.44, Neher et al. =4.7) and organic carbon in RM was much higher (RM organic carbon=30.26%, Neher et al. SO M=8.4). Using one standard conversion factor for OC to SOM, 1.74 (Nelson and Sommers, 1982), the contrast between RM (53% SOM) and Neher et al. (8.4% SOM) is more pronounced. It must be noted, however, that soil samples for Neher et al. went to a depth of 20 cm and probably did not include the surface litter layer.

2. Litter Microarthropods

Methods

Microarthropods were extracted from litterbags using a modified Tullgren funnel apparatus (Mallow and Crossley, 1984). Litterbags were left on the funnels for 3 to 4 days; the extracted microarthropods were preserved in 70% ETOH. Microarthropods were sorted under a stereo microscope into the following categories: oribatid, prostigmatid, and mesostigmatid mites, Collembola, and others. Microarthropod abundances were determined as the mean number of animals/g dry litter.

Since the abundance values of soil microarthropods were not normally distributed, the data were analyzed using a Generalized Linear Model (Proc Genmod SAS version 9.1, 2005) (Littell et al., 2002). However, since the numbers of collembola were so low, the date*site term was not used due to overfitting of the data. The model without date*site term was suitable for over-dispersion of these collembolan data (Allison, 2001). Standard errors and Tukey lines in microarthropod graphs are provided for comparison purposes, but are not statistically rigorous because the data break the assumptions of normality.

Results and Discussion

Microarthropod numbers varied significantly with date (Table 13). We also found significant differences in litter microarthropod numbers by site for total microarthropods and all individual taxa except for Prostigmatida, which were not abundant enough for statistical analysis (Table 13, Fig. 11). The average number of Prostigmatida/g dry litter ranged from 3.0 at CF to 1.2 in OF and FP. Similar seasonal variations in microarthropod numbers have been reported for upland hardwood forests in the southern Appalachians (Reynolds et al., 2003; Brennan, 2003). Date*site interactions were not significant for total microarthropods nor the most abundant taxon, Oribatida (Table 13). Although there were significant date*site interactions for the Mesostigmatida, thus confounding interpretation of significance by site, the low numbers of Mesostigmatida, similar to even lower numbers for Collembola and Prostigmatida, call into question the significance of these taxa for the present study, especially when compared to the abundance of the Oribatida.

Table 13. Microarthropod responses to date and site. Data analyzed were average numbers of microarthropods per gram of red maple litter from litterbags in the field for seventeen months (Jan, 2003 to May, 2004). **No values are presented for Collembola date*site due to over-fitting of the data with that term in the model.

Organism	Log-Likelihood	Terms	Chi-square	df	P
Total	1213.55	Date	43.30	7	<.0001
		Site	52.38	4	<.0001
		Date*Site	38.28	28	0.0932
Oribatida	946.16	Date	36.62	7	<.0001
		Site	43.42	4	<.0001
		Date*Site	39.85	28	0.0682
Mesostigmatida	357.81	Date	61.37	7	<.0001
		Site	39.95	4	<.0001
		Date*Site	44.93	28	0.0224
Collembola	119.02	Date	51.30	7	<.0001
		Site	47.26	4	<.0001
		**			

In all sites, oribatid mites were by far the most common microarthropod (Fig. 11) and they were most abundant in the RM community. Abundances of oribatids (and total microarthropods) appear to be significantly lower in FP and DA. The proportion of Collembola to Oribatida is much lower in Tulula samples than that reported for upland hardwood forests in the southern Appalachians (Reynolds et al., 2003; Knoepp et al., 2005), although numbers for total microarthropods are far greater at Tulula than in upland forests. Similar relations between collembolan and oribatid numbers were found in soil cores from the same vegetation sites at Tulula (Hamel and Reynolds, unpublished data). We assume that the relatively wetter soils at Tulula have a dampening effect on collembolan populations. Braccia and Batzer (2001) found collembolan numbers to be roughly one-quarter those of all acarina in a study of arthropods associated with woody debris in a forested wetland in the southeastern U.S.; collembola numbers in our samples were approximately one-tenth those of acarina. Although soil pH was relatively low for all sites, many species of collembolans are reported to be acid-tolerant (Cassagne et al., 2003). Thus, although differences in soil pH may have influenced the distribution of collembolans among our sites, we do not believe that their relatively low numbers compared to other areas are due to low soil pH.

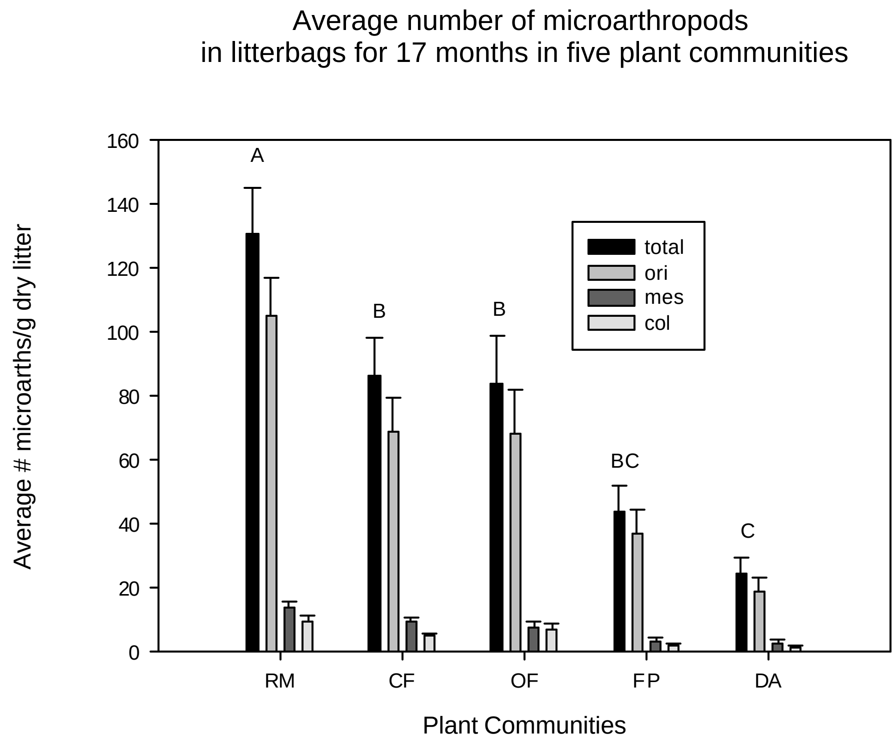

Fig. 11. Average number of microarthropods/g dry red maple litter for 17 months. Plant communities are RM=red maple, CF=closed fen, OF=open fen, FP=flood plain, and DA=disturbed alluvial bottomland forest. Each bar is the average of 38 to 46 litterbags; error bars are ± 1 SE. Means with the same letter are not significantly different; but see text.

A comparison of litter microarthropods was made in March, 2003, before canopy closure to determine if presence/absence of the canopy affected numbers of microarthropods. We found that even before canopy closure there were fewer microarthropods in the DA and FP sites (Fig. 12). In addition, we found a strong negative correlation with soil pH (-0.63) and a strong positive correlation with soil organic carbon (0.60) (Table 12) for total microarthropods. Soil organic carbon was highest in RM and soil pH was significantly lower in RM. Neher et al. (2003) also found a lower pH in wetland soils from an undisturbed site compared to a disturbed area.

Summary of Decomposition and Soil Fauna

What characteristic of the RM site could explain the differences we measured in percent litter remaining, total microarthropod numbers, highest organic carbon and lowest pH? We conclude that these measurements are all indicators of an undisturbed soil, and that the high rate of decomposition and high total microarthropod numbers are functions of an older, least disturbed, ecosystem.

These findings could be related to the presence of a canopy in RM and CF, protecting litter-dwelling arthropods from extremes in temperature and from desiccation when exposed to solar radiation. However, the low numbers of total microarthropods in DA and FP, compared to sites with more canopy (RM, CF, and OF), even before leaves are present in March, 2003, indicates that other factors are involved. We posit that soil disturbance, once again, plays a major role in a critical ecosystem factor – the abundance of litter microarthropods.

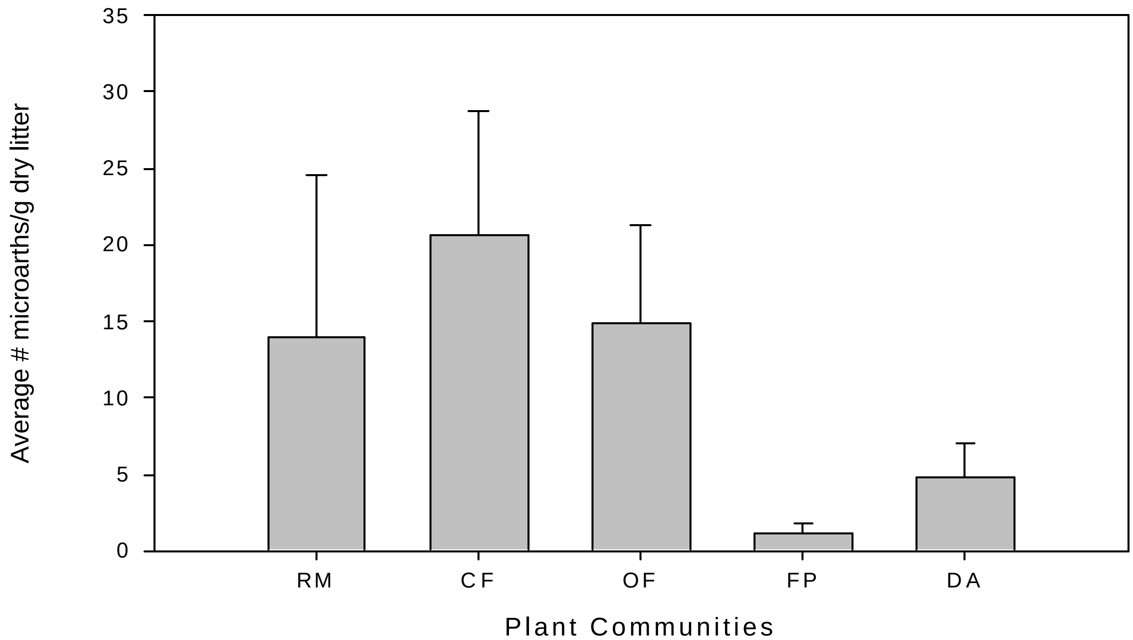

Fig. 12. Average number of total microarthropods/ g dry red maple litter for March, 2003. Plant communities are RM=red maple, CF=closed fen, OF=open fen, FP=flood plain, and DA=disturbed alluvial bottomland forest. Each bar is the average of 6 litterbags; error bars are ± 1 SE.

D. *Assessment of Restored Amphibian Habitats*

Introduction

Amphibians are increasingly being used as indicator species in restoration projects for small freshwater wetlands (e.g., Pechmann et al. 2001) because they are often community dominants, are sensitive to site hydrology, and can be easily monitored to assess ecosystem function. Amphibians play key ecological roles in wetlands in the southern Appalachian Mountains, and are the dominant vertebrate group in standing water habitats at Tulula. Because a major goal of wetlands restoration is to restore ecosystem integrity (e.g., to create functional ecosystems where all major community elements are sustained at viable levels), the response of amphibians to site restoration is a useful indicator of ecosystem function.

Because of their strong reliance on seasonal wetlands for breeding, the reproductive success of many amphibian species is strongly influenced by hydroperiod (seasonal duration of ponds). The hydroperiod affects the likelihood of amphibian larvae reaching a minimum developmental stage to complete metamorphosis. It also influences the distribution and abundance of predators such as fish and aquatic insects that feed on amphibian eggs and larvae. Short hydroperiods during periods of drought can result in catastrophic mortality of larvae due to premature pond drying, but also reduce or eliminate aquatic predators. Long hydroperiods during wet years provide ample time for amphibian larvae to complete metamorphosis, but may result in heavy mortality from predators such as dragonfly larvae that prefer semi-permanent ponds.

At the initiation of the study in 1994, the site contained aquatic habitats that varied from highly ephemeral to permanent ponds. Most natural breeding sites were filled during golf course construction. During a detailed survey of the site during 1994-1995, we located 155 standing-water habitats that included 11 permanent ponds that were constructed as golf course obstacles. Permanent ponds contained predatory fish (bluegills, largemouth bass) and were not used as breeding sites by most resident amphibians. The remaining 144 sites were fish-free, seasonal habitats that were mostly small, shallow depressions. These included mud puddles, water-filled tire ruts, test wells for pond sites, sluggish ditches, and stream cut-offs associated with the channelization of Tulula Creek.

Monitoring of seasonal habitats during 1994-1995 indicated that most breeding sites were of very low quality because of altered site hydrology associated with stream channelization, ditching, and the filling of low-lying areas. All species of vernal pond-breeders suffered high larval mortality during 1994 and 1995 because most breeding sites dried prematurely before tadpoles or salamander larvae could complete their larval stages. Despite heavy rains in late winter and early spring, about 75% of the breeding sites dried prematurely in 1994 and 60-70% in 1995. These observations indicated a need to construct larger and deeper ponds to replace natural breeding sites that were destroyed during golf course construction.

Ten vernal ponds were constructed between October 1995 and January 1996 to replace natural breeding habitats. Depth and contour were manipulated to create seven temporary and three permanent fish-free ponds that provide suitable habitat for all pond-breeding amphibians at Tulula. At seven sites small standing water habitats existed prior to the construction of ponds. We selected 10 of the largest existing breeding sites as reference ponds to compare hydrological, physiochemical, and biotic characteristics. One reference pond was destroyed in 2001 in conjunction with reconstruction of the stream channel. Two others did not fill in 2001-2002 due to construction activity, but were functional from 2003-2006.

Thirteen new breeding sites were also created in the fall of 1999 when golf course ponds were either filled or partially filled to create shallow ponds. Most of these were stream-fed, and now exist as shallow, permanent sites that contain small fish. In others, fish were eliminated and the sites were converted into temporary ponds. Sections of the restored stream channel also were temporarily blocked with check dams to allow channel re-vegetation prior to restoring stream flow. Small pools formed in the deepest sections of these channel segments and were used as breeding sites by resident amphibians in 2001. Additional pools were formed in conjunction with stream and site restoration in 2001-2003. In February 2006 the site contained over 60 breeding sites (Fig. 13).

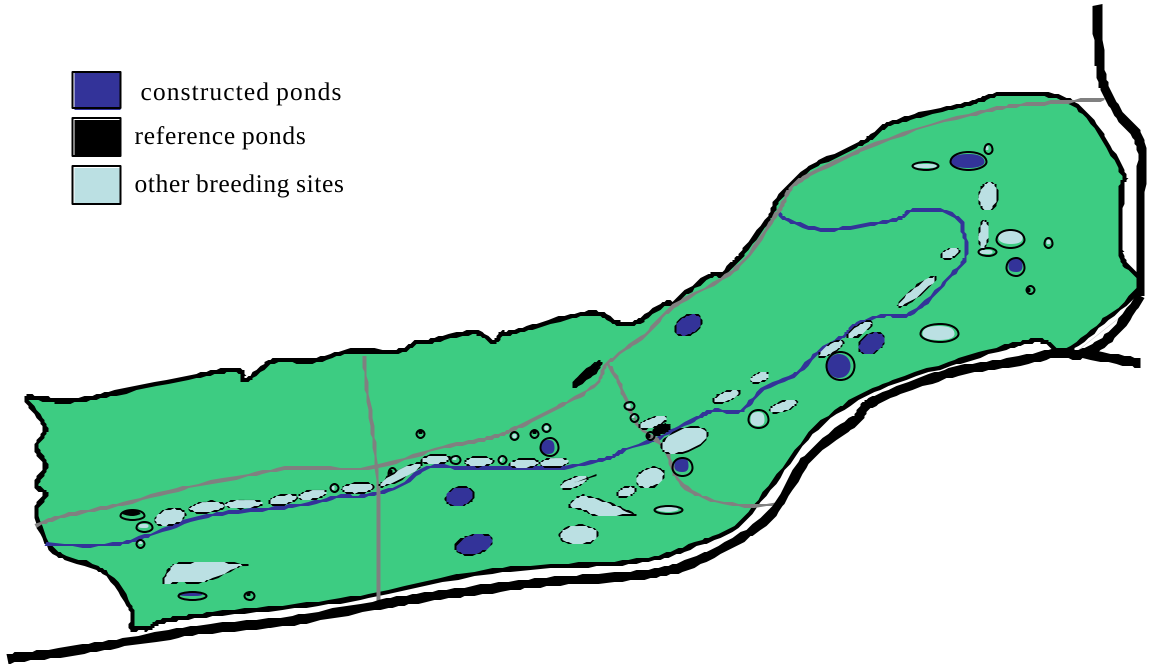

Fig. 13. Location of standing water habitats within the study site (spring 2006).

Methods

The 10 constructed and 10 reference ponds were sampled 3-19 times annually to obtained data on pond pH, temperature, conductivity, and oxygen saturation. Samples were taken during the day (900-1700 hrs) and all constructed and reference ponds were sampled haphazardly during the same day. Three subsamples of water were taken from each pond at approximately equidistant points along the center of the long axis and approximately 10 cm below the water's surface. Subsamples were pooled and readings were taken from the pooled sample. Samples were placed on ice during warm weather and dissolved oxygen was measured in the field < 3 hours after samples were collected using Corning Check-mate meters. Conductivity and pH were measured using Corning Check-mate and Corning 430 bench meters, respectively. We used the yearly mean for seasonal samples in statistical comparisons of reference and constructed ponds.

Results

Reference ponds were smaller and shallower than constructed ponds, which could influence physiochemical characteristics. At full capacity, surface areas of reference ponds averaged 888 ft^2 (range = 145-2367 ft^2) versus 5165 ft^2 (range = 2421-9931 ft^2) for constructed ponds. Respective values for maximum depths were 13.4 inches (range = 5.1-23.6 inches) and 24.4 inches (range = 15-34 inches). Comparisons of physiochemical characteristics of constructed and reference ponds from 1996-2006 are in Fig. 14.

Respective grand means (+ 1 SE) based on annual averages for reference versus constructed ponds for 1996-2006 were 5.46 (0.05) versus 5.58 (0.03) for pH, 13.7^{o}C (0.35) versus 16.0^{o}C (0.36) for temperature, 42.9 (3.25) versus 38.0 (2.27) dS/cm for conductivity, and 58.3 (2.1) versus 78.2 (1.6) for percent O_2 saturation. T-tests (alpha = 0.05) indicate that means for pH differed only in 2002 and 2004, while conductivity did not differ significantly for any year (conductivity: $P > 0.19$). However, constructed ponds were significantly warmer in 7 of 10 years and had significantly higher oxygen saturation levels in all but two years (Fig. 14).

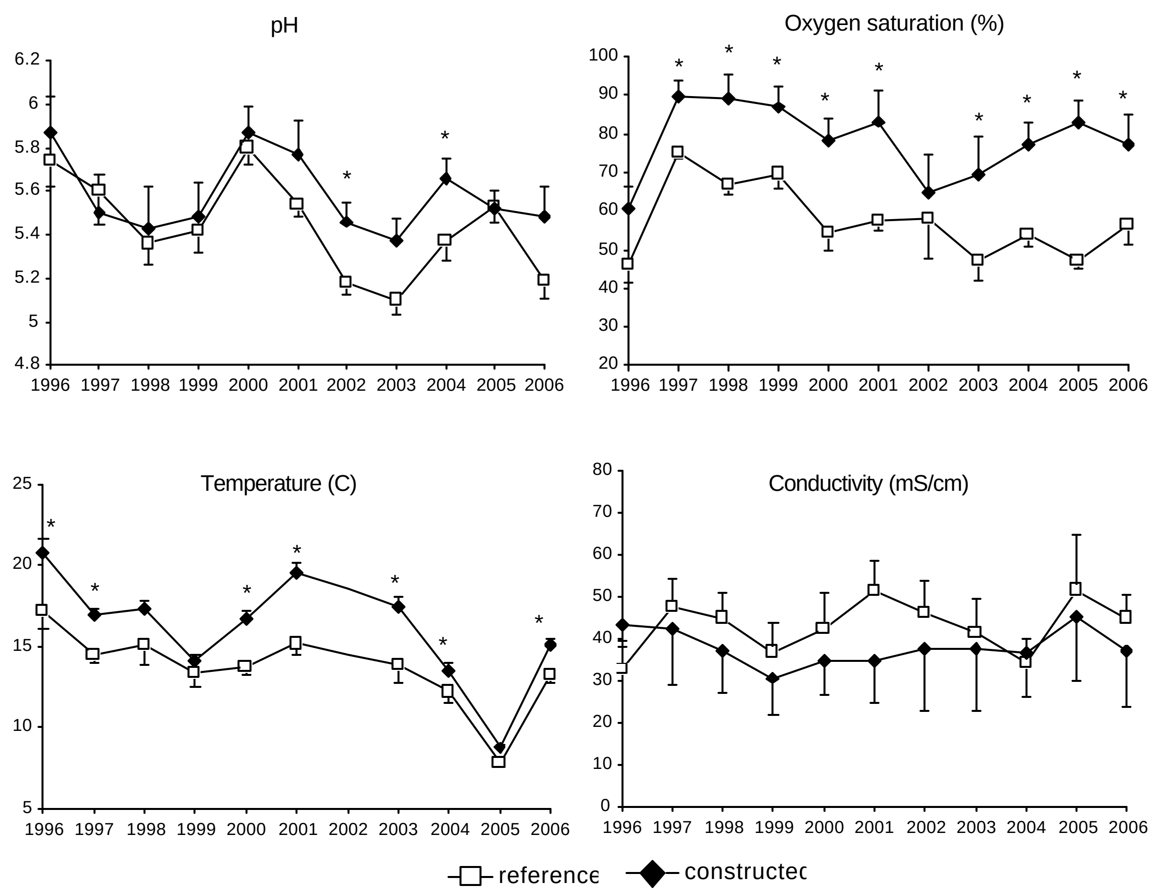

Fig. 14. Physiochemical characteristics of reference and constructed ponds. Symbols are annual means based on 3-19 seasonal samples per year. Vertical bars are 1 SE. Asterisks indicate means that differed significantly within years.

2. Use of constructed and reference ponds by amphibians.

Methods

All constructed ponds filled with water before amphibians began breeding in February 1996. We monitored all constructed and reference ponds annually to determine patterns of use by resident species. We visited ponds every 1 to 3 weeks between January-August and searched for amplexed adults, eggs, or larvae. Larvae were collected when conducting open-bottom sampling to estimate survival (see below) and when ponds were dip-netted periodically during the spring and summer to sample resident amphibians.

Results

Resident amphibians rapidly colonized constructed ponds that first filled in 1996 (Fig. 15B). Eight species of amphibians bred in the constructed ponds within 1 year of construction and 10 species have used the ponds through 2006. These are the wood frog, green frog, bullfrog, gray treefrog, spring peeper, American toad, spotted salamander, red salamander, three-lined salamander, and the red-spotted newt (Appendix D). The only species unique to constructed ponds was the American bullfrog, which prefers permanent or semipermanent habitats. Reference ponds were also used by 10 species of amphibians and only one, the two-lined salamander, was unique to reference ponds (breeding in 1 of 10 reference ponds). The completion of reconstruction activities, average or above average precipitation in 2003-2006, and invasions of the site by beavers have increased the number of habitats with fish.

Damming of Tulula Creek by beavers caused spillover into most of the nearby wetlands that parallel the stream on the west end of the site. Almost all of these sites now contain fish and provide little habitat for seasonal pond breeders. Although reference ponds are too ephemeral to support fish, fish have invaded many of the constructed ponds since 2002 (Fig. 15A). Amphibians that use fish-free habitats have responded by not ovipositing in ponds with fish (Petranka and Holbrook 2006); however, it is uncertain whether adults that avoid ponds with fish are successfully breeding in other habitats on site.

Overall, constructed ponds contained a significantly greater number of breeding species (mean + 1 SE = 3.89 + 0.17 species) than reference ponds (2.83 + 0.17 species) during the 11-year period (paired t-test; $P < 0.0001$). For individual years, the mean number of species per pond was significantly higher in constructed ponds in five of eight years and approached significance ($P < 0.10$) for two other years (Fig. 15B). Regression analysis indicates that the mean number of species using ponds annually did not increase between 1996-2005 (P values for reference and constructed ponds = 0.33 and 0.54, respectively). The latter suggests that constructed ponds quickly reached saturation levels within one year of construction. A more detailed analysis of pond colonization and community turnover is in Petranka (2000a).

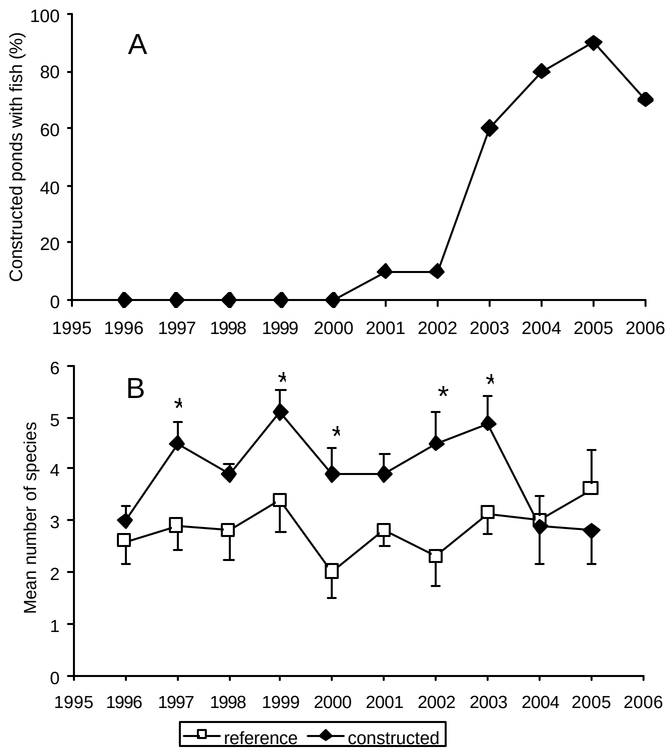

Fig. 15. Relationship between the long-term colonization of fish in constructed ponds (A) and (B) the mean number of species that bred in reference and constructed ponds. Symbols are means and bars are + 1 SE. Years with asterisks are significantly different.

3. Response of focal species to constructed ponds.

Methods

We selected the spotted salamander (*Ambystoma maculatum*) and wood frog (*Rana sylvatica*) as focal species for monitoring ecosystem function and restoration success. Both species are widely distributed across the site and are largely restricted to temporary ponds that predominated prior to golf course construction. These species lay large egg masses that can be accurately counted, and that serve as an index of the size of the female breeding population.

To obtain estimates of the overall response of the focal species to restoration efforts, we conducted a complete count of egg masses on the eastern half of the site beginning in 1995. This census included the 10 constructed ponds, the reference ponds, and all other breeding sites in the eastern sector.

To estimate relative changes in embryonic and larval survival across years, we estimated the total population size of hatchlings and larvae nearing metamorphosis in each pond using open-bottomed samplers. Populations were sampled using 30 gallon galvanized trashcans with bottoms that were removed with a blowtorch (approximate area of can bottom = 1.2 ft^2). When sampling, the can was pushed into the pond substrate to trap larvae. Repeated sweeps of the can were made with aquarium nets until no larvae were captured for five consecutive sweeps.

Ponds were sampled by walking a zig-zag transect across the entire area of the pond and taking samples at approximately equidistant points along the transect. The number of samples per pond increased with pond size and varied from 15-80. If ponds were not at full capacity, then pond surface area was estimated at the time of sampling based on 3-5 measurements of length and width using a meter tape. The total population size of hatchlings or larvae nearing metamorphosis was estimated using data on the mean number of larvae per sample, the surface area of the sampler, and the surface area of the pond.

We obtained an initial sample of hatchlings within 1-3 weeks after > 95% of the egg masses were estimated to have hatched in a pond. We intensively dip-netted ponds as larvae approached metamorphosis, and obtained a final sample immediately after the first metamorphosing larva was observed in each pond. Criteria used to recognize metamorphosing larvae were the emergence of both front legs for wood frog tadpoles and the partial or complete reabsorption of gills and dorsal fins for spotted salamander larvae. We used this estimate as a relative measure of the number of juveniles that were recruited into the terrestrial population each year.

Changes in adult population size are the most meaningful measure of the response of amphibians to site restoration efforts. However, a significant time lag in population responses occurs because of the prolonged juvenile stage. That is, juveniles that metamorphose and leave ponds may not return for 2-4 years as breeding adults. We used total egg mass censuses of the eastern half of the site to measure the effects of pond construction and site restoration on breeding populations.

Results

The responses of breeding populations of wood frogs and spotted salamanders to pond construction are shown in Fig. 16. These data exclude two constructed ponds (7X; 10X) that occurred on the western end of the site and three small reference ponds that were either destroyed (2C) or were nonfunctional in 2002 (3C; 4C) and 2003 (4C only) due to construction activities. During 1996 (first year after pond construction and filling), 71% of the resident wood frogs and 59% of spotted salamanders bred in the constructed ponds. A corresponding decline in breeding effort occurred in the remaining small depressions, suggesting that many adults abandoned historical breeding sites in favor of newly constructed ponds.

The percentage of adult wood frogs that bred in constructed ponds between 1996 and 1999 increased slightly. However, adults decreased use of constructed ponds after 1999 and shifted to other sites. This reflects a progressive increase in the number of ponds on site in association with stream and final site reconstruction, and the lack of use of ponds that were colonized by fish (Petranka and Holbrook 2006). Overall, the percentage of eggs laid in constructed ponds decreased significantly between 1996-2006 (regression analysis: $P = 0.002$; $r^2 = 0.66$). In contrast, use of constructed ponds by spotted salamanders was similar across years ($P = 0.15$), perhaps because adults favor larger, deeper ponds for breeding. In 2006, approximately 26% of wood frogs and 41% of spotted salamanders bred in the constructed ponds, while reference ponds provided breeding habitat for < 15% of the population.

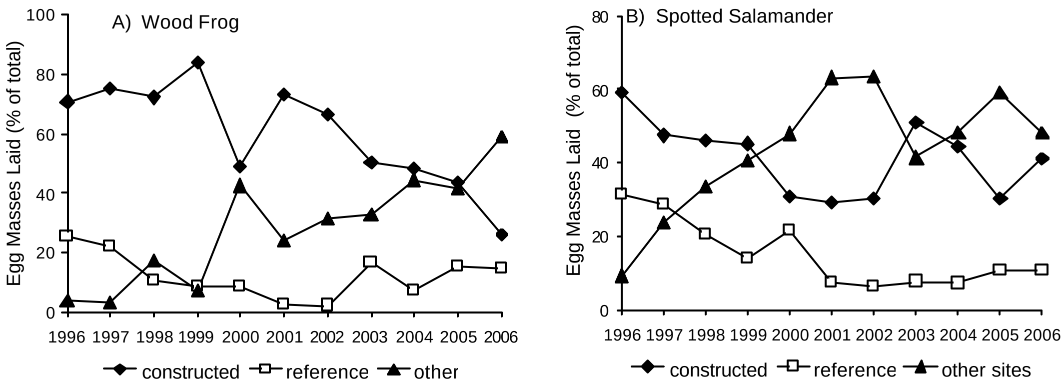

Fig. 16. Responses of female wood frog and spotted salamanders to pond construction. Symbols are the number of egg masses laid on the eastern half of the site in constructed ponds, reference ponds, and all remaining breeding sites. Numbers are expressed as a percentage of all masses laid in the eastern half of the site. ‘Other” includes all sites other than reference and constructed ponds, including sites that were created during stream channel restoration.

Fig. 17 shows annual changes in the percentage of ponds that successfully produced juveniles (upper graphs) and total yearly output of juveniles from constructed and reference ponds (lower graphs). The overall respective percentage of ponds that successfully produced juveniles for wood frogs and spotted salamanders declined annual from 90% and 75% in 1996 to < 35% after 1997. The estimated output of terrestrial juveniles from constructed ponds was exceptionally high during 1996 (N = 253,696 wood frogs; 30,831 spotted salamanders), but progressively declined in later years. A similar trend occurred in reference ponds. These trends parallel a general decline in the percentage of ponds that have successfully produced juveniles each year. Nonetheless, a small percentage of ponds on site have successfully produced juveniles annually, and viable populations of both species occur on site. Since 2002, reference ponds have generally been more successful in producing juveniles than constructed ponds. This reflects the widespread invasion of fish into constructed ponds and the increased hydroperiod of reference ponds during 2003-2005.

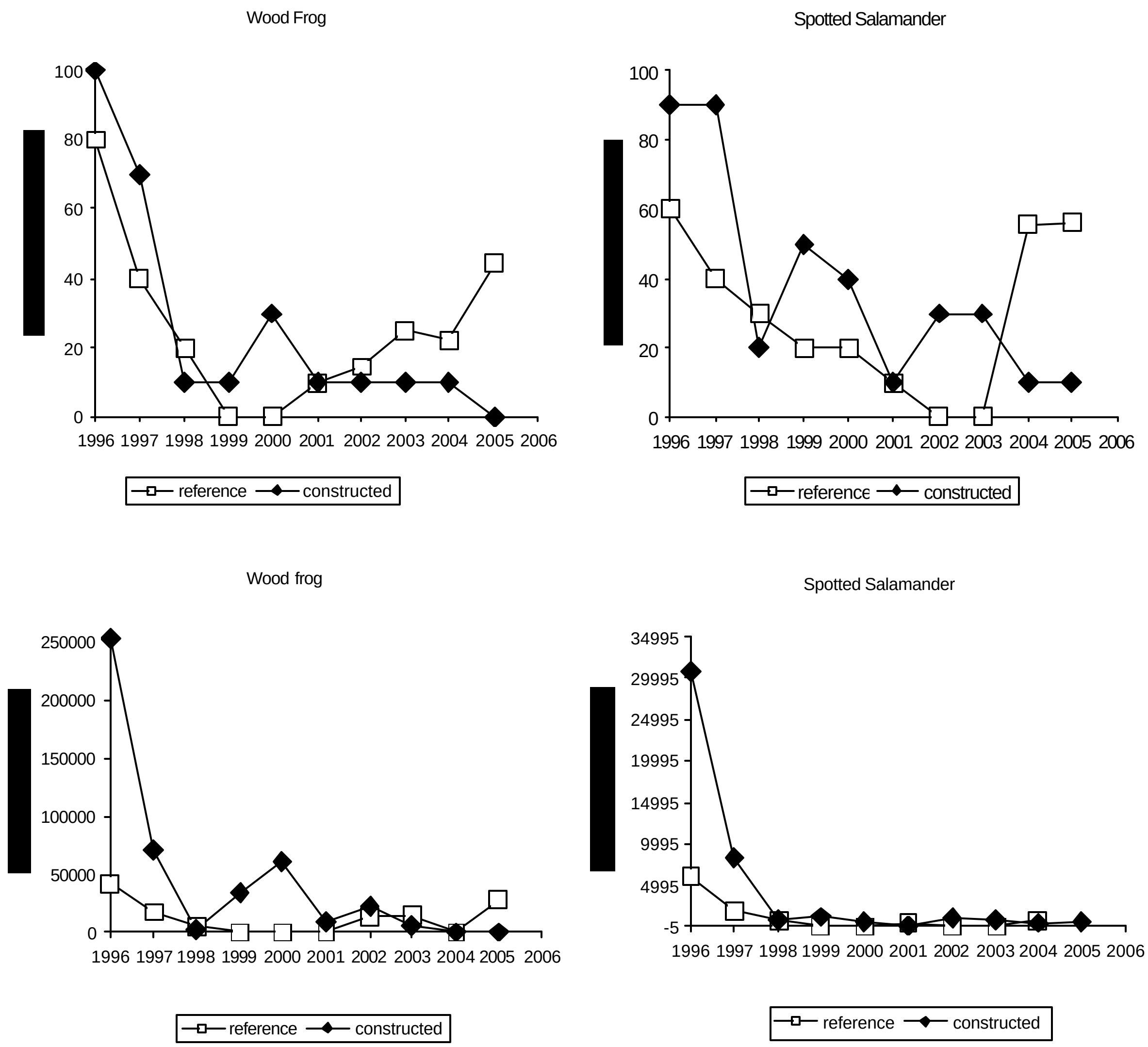

Fig. 17. Estimates of the percentage of ponds that produced juveniles, and total juvenile recruitment from 10 constructed and 10 reference ponds during 1996-2005. Symbols for upper panels are the percentage of ponds that produced juveniles annually, whereas those in the lower panels are the estimated number of larvae surviving to the initiation of metamorphosis.

Comparisons of the number of hatchlings and number of larvae surviving to the initiation of metamorphosis (see Petranka 2003b for details) indicate that the decline in juvenile output was primarily due to increased larval mortality rather than increased embryonic mortality. Embryonic survival varied among years, but there was no evidence of catastrophic mortality for any year. In contrast, overall juvenile production per egg mass declined markedly during the study period for both species and both sets of ponds. The reduction in juvenile production is attributable to at least three factors: (1) premature pond drying and/or the failure of ponds to fill seasonally during periods of drought, (2) outbreaks of a pathogen that caused larval die-offs, and (3) the accumulation of predators in constructed ponds after 1996.

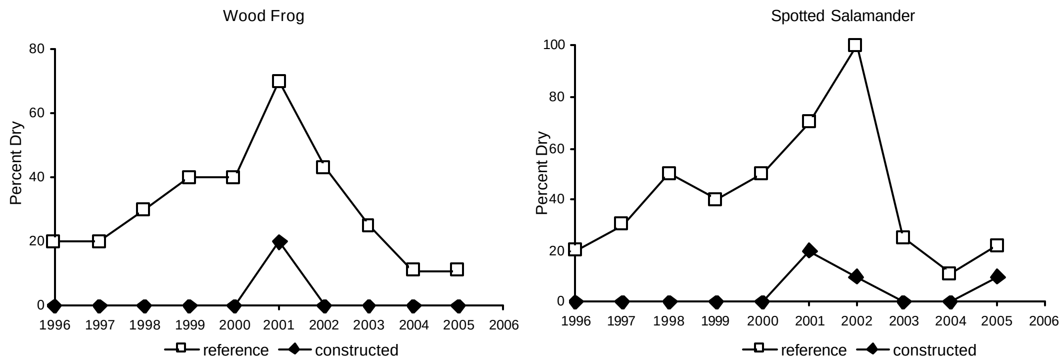

Fig. 18. Annual variation in the percentage of constructed and reference ponds that either did not fill or that dried before larvae could initiate metamorphosis.

Fig. 18 shows the percentage of ponds that either did not fill or that filled and dried prematurely between 1996-2005. Constructed ponds filled annually and usually held water sufficiently long to allow metamorphosis of both species. An exception is 2001 when two ponds dried prematurely, causing catastrophic mortality.

The more shallow reference ponds tended to progressively deteriorate with respect to hydroperiod between 1996-2002. During 2002, 43% and 100% of the reference ponds either did not fill or dried prematurely for *Rana* and *Ambystoma*, respectively. This pattern may in part reflect a regional drought that occurred from the summer 1998 and fall 2002. The proportion of reference ponds that dried prematurely decreased after 2001-2002 as the drought ended and rainfall increased to average or above average levels.

Disease is a second factor that contributed strongly to the decrease in juvenile output. Outbreaks of a disease that caused catastrophic larval mortality were first observed in 1997. Moribund specimens were sent to the National Wildlife Health Center in Madison, Wisconsin, and detailed histological and molecular studies (Harp and Petranka 2006) revealed that the pathogen is an iridovirus (*Ranavirus*).

Larvae of both the wood frog and spotted salamander are susceptible to *Ranavirus* infections. Infected larvae tend to become lethargic, often float at or near the water surface, and develop characteristic bloody, hemorrhagic patches on the body and fins. Infected larvae are first noticed seasonally during the mid- to latter half of the larval stage. Catastrophic mortality typically occurs within 1-2 weeks after the first infected individuals are detected. Typically, outbreaks result in 100% mortality of larvae in a pond.

The extent to which the disease has impacted local populations of wood frogs and spotted salamanders is shown in Fig. 19. Diseased animals and die-offs were not observed prior to 1997, at which time two die-offs occurred in two ponds. The disease rapidly spread to other ponds on site, became a major source of larval mortality from 1998-2000, and subsequently declined.

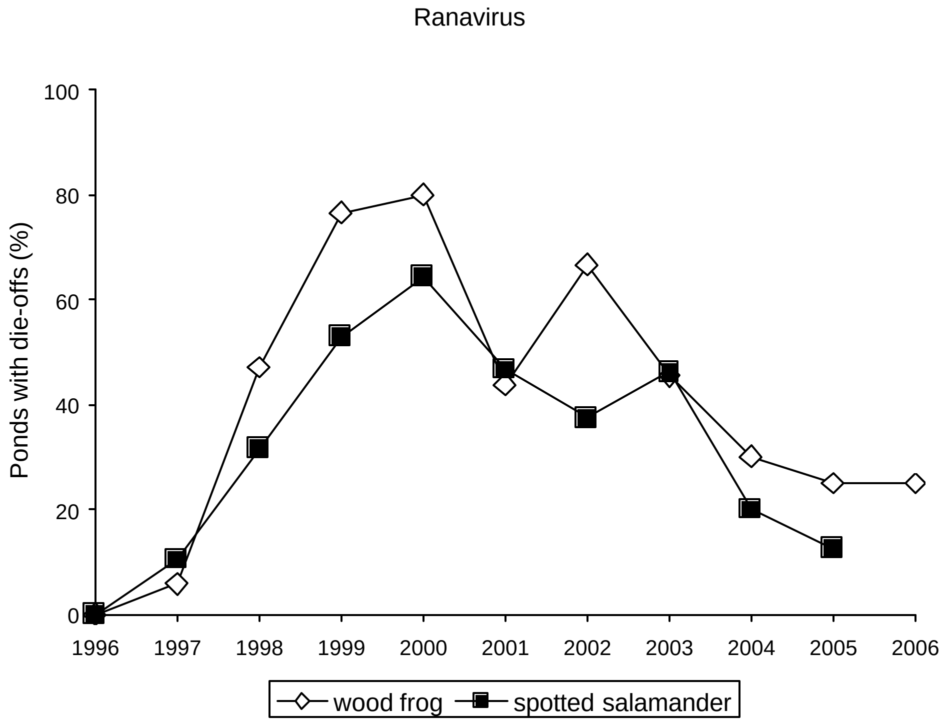

Fig. 19. Changes in the percentage of reference and constructed ponds in which catastrophic die-offs of larvae occurred from *Ranavirus* infections.

Egg and larval predation was the third significant source of premetamorphic mortality that contributed to the decline in juvenile output between 1996-2006. In particular, egg predation by green frog tadpoles on wood frogs (Petranka and Kennedy 1999), and wood frog tadpoles on spotted salamanders (Petranka et al. 1998) were significant sources of mortality in certain ponds. Odonates and other predatory aquatic insects accumulated in constructed ponds after 1996 and presumably contributed to higher larval mortality. The incidence of fish in constructed ponds increased dramatically after 2002 (Fig. 15A) and has impacted seasonal pond species, both directly through predation on larvae, and indirectly via breeding adults actively avoiding habitats with fish (Petranka and Holbrook 2006).

Despite impacts from drought, disease, and predators, populations of both focal species have not suffered severe crashes and have remained at viable levels (Fig. 20). The size of the wood frog population declined from 1995-1998, increased dramatically (366%) through 2000, and declined thereafter. The population has remained relatively stable since 2002. Female wood frogs require 3-4 years to reach sexual maturity after metamorphosing (Bervin 1982). Thus, the marked increase in population size in 1999 corresponds to when the large output of juveniles in 1996 first returned to breed as adults. The decline since 2000 presumably reflects the impact of *Ranavirus*, premature pond drying, and fish invasions on annual juvenile recruitment.

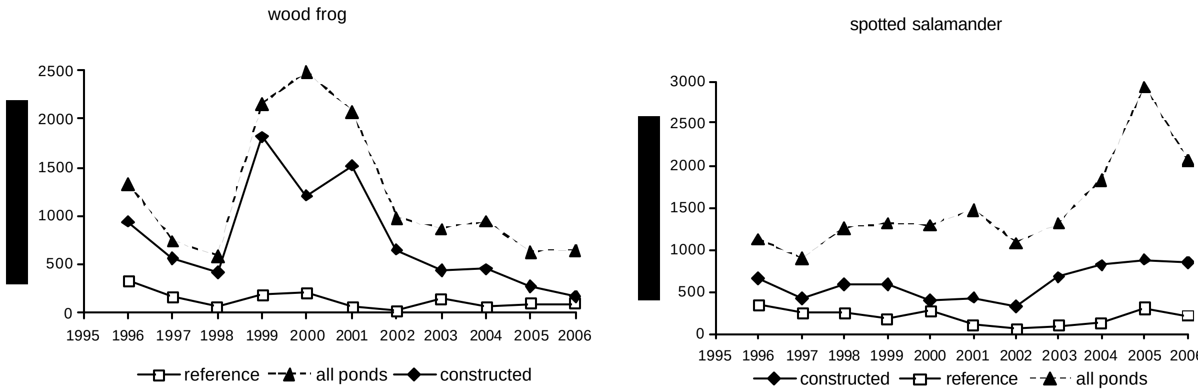

Fig. 20. Changes in adult breeding population size on the eastern sector based on annual egg mass counts in all breeding sites.

The population of spotted salamanders has not changed as markedly. The size of the breeding population slowly increased from 1995 (N = 1,265 egg masses) to 2005 (N = 2,931 egg masses). Females of this species may require 3-5 years to reach sexual maturity (Petranka 1998), so the gradual increase in breeding population size may reflect recruitment from the relatively large output of juveniles in 1996 and 1997. The decline in 2002 may reflect the impact of *Ranavirus* outbreaks that began in 1997-1998. However, in 2005 the population reached its highest level, indicating that annual recruitment into the terrestrial population has been sufficient to gradually increase adult population size.

Summary

Amphibians often exhibit boom-and-bust recruitment patterns in which juvenile recruitment from local ponds may be near zero in some years and high in others (e.g., Gill 1978, Semlitsch et al. 1996). Local populations are buffered from these effects since the adults may live many years and metapopulation dynamics allow for some recruitment annually. Thus, years with complete reproductive failure in local ponds may not necessarily translate to long-term declines of local populations.

Our design strategy at the Tulula Wetlands was to install a complex array of seasonal, semipermanent, and permanent habitats that would provide habitats for the diverse species assemblage on site, and that would increase population resilience in response to perturbations associated with drought, fish invasions, the outbreak of disease, and altered hydrology from beaver activity. Data collected from 1996-2006 indicate that both focal species have been resilient to environmental perturbations and have maintained relatively large breeding populations despite catastrophic mortality that often occurs in individual ponds in a given year.

Reference ponds have generally been unproductive during years with drought, since these are the most shallow habitats and have short hydroperiods. In 2002, for example, the majority either did not fill or dried prematurely, resulting in catastrophic mortality of pond populations. In contrast, the hydroperiod of most constructed ponds appears to be adequate for most vernal pond breeders. Seven of 10 ponds normally undergo seasonal drying in late summer or fall when larvae have metamorphosed. However, fish have colonized many since 2002 in association with above normal rainfall, beaver activity, and completion of the final phase of reconstruction. By having ponds that vary markedly in hydroperiod, a small subset of ponds have produced juveniles each year at rates that appear to be sufficient to maintain viable breeding populations of both species.

Scientists currently know very little about the epidemiology of amphibian *Ranavirus*. For example, researchers do not fully understand how the virus is transmitted among hosts, whether a subset of larvae is resistant to the virus, or whether the infections subside after several years of outbreaks. Outbreaks of *Ranavirus* have dramatically reduced the output of juveniles from both constructed and reference ponds. Similar outbreaks of this disease have been reported in several areas of the United States (Daszak et al. 1999) and have resulted in catastrophic die-offs of larvae. Our long-term data suggest that the impact of ranaviral disease may subside after strongly impacting local populations for the first few years after an outbreak.

The invasion of beavers (*Castor canadensis*) and the completion of stream restoration are influencing site hydrology and the dynamics of amphibian populations at Tulula. Beaver invaded the site shortly before stream channel construction began and were eliminated through trapping. They have since reinvaded and have significantly altered the landscape. Fish have become far more abundant on site since 2002 and have invaded most of the constructed ponds. In general, habitat quality for amphibians that use seasonal wetlands has declined in association with beaver activity. However, seasonal pond specialists compensate by avoiding sites with fish and seeking alternative breeding sites that are fish-free.

E. Bird Response to Restoration

Birds are used as a common indicator for assessing changes in habitat attributes that are associated with many types of restoration projects (Morrison 1986). Since 1994, we have conducted breeding bird surveys of the Tulula floodplain (Rossell et al. 1999, Moorhead et al. 2001a). Restoration of Tulula Creek was completed during the summer of 2002. Here we report results of breeding bird surveys conducted during 2006. These results represent the response of bird populations after four years post-restoration at Tulula. As a result of budget constraints, habitat data were not collected in 2006.

1. Bird Surveys

Methods

Breeding bird surveys were conducted from 17 May to 24 May 2006, at 32, 82-ft radius plots located across Tulula floodplain. Plots covered most of the floodplain and were separated by at least 328 ft to avoid double counting birds (Pendleton 1997). Surveys were conducted from sunrise until 1000 hrs. After a 1-min quiet time, all birds heard or seen within 82 ft of the plot center were recorded for 3 min. Birds that flushed within 82 ft of the plot center during the approach also were recorded. Each plot was sampled three times during the survey period. Bird richness was defined as the total number of species, and relative bird abundance was defined as the total number of individuals of a species.

Results and Discussion

Results of breeding bird surveys from 1994 to 2006 are presented in Table 14. Belted Kingfisher, Hermit Thrush, Palm Warbler, and Wood Duck were new species recorded during breeding bird surveys in 2006 (See Appendix E for complete list of birds and scientific names). Belted Kingfisher and Wood Duck were probable breeders on site, while Hermit Thrush and Palm Warbler were late migrants and not breeding on site.

Species richness of breeding birds in 2006 remained essentially the same as in 2004, with 30 species recorded (excluding Hermit Thrush and Palm Warbler), and was consistent with pre-restoration levels in 1994 and 1998 (Table 14). Relative bird abundance in 2006 increased 14% from 2004, with 103 total observations (Table 14); however, relative abundance of birds in 2006 was 28% and 41% less than pre-restoration levels in 1994 and 1998 (Table 14). In 2006, Red-winged Blackbird was the most abundant bird on site, followed by Acadian Flycatcher, Hooded Warbler, and Red-eyed Vireo, while Kentucky Warbler declined the most since 2004. Other species that decreased in abundance or remained at relatively low numbers in 2006 included Golden-winged Warbler and Yellow-breasted Chat. Also notable, was the Brown-headed Cowbird, which was breeding at Tulula in 2002, but was not observed on site in 2006.

Habitat of the Tulula floodplain has changed substantially since the pre-restoration period of 1994-1998. A primary factor for this change is colonization of the site by beaver. As a result of beaver activity, approximately one-third to almost one-half of the floodplain at the western-end of the site has become inundated with water. Flooding of the site began in 2002 after stream construction was completed and has continued through 2006. The presence of standing water has resulted in the loss of herbaceous habitat as well as a loss of shrub and a live- canopy component. In addition, natural succession, particularly at the eastern end of Tulula and in some of the fairways, has resulted in a further loss of shrub and edge habitat, which has been replaced by a single–age stand of saplings dominated by white pine and some red maple. These habitat changes are reflected in the general differences of the species composition of birds (pre- vs. post-restoration) at Tulula (Table 14). For example, species associated with water, including Red-winged Blackbird, Acadian Flycatcher, Belted Kingfisher, and Wood Duck (Hamel 1992), have become more abundant, while species associated with early successional habitats, particularly those with an affinity towards shrub and edge habitats, have declined (e.g., Golden-winged Warbler, Hooded Warbler, Indigo Bunting, Kentucky Warbler, Swainson's Warbler, White-eyed Vireo, and Yellow-breasted Chat). In addition, many of these early-successional species are neotropical migrants of conservation concern (Hamel 1992).

The species of highest conservation concern at Tulula is the Golden-winged Warbler. The Golden-winged Warbler is federally-listed as a species of special concern (LeGrand and Hall

2004). Since 1994, the Golden-winged Warbler has decreased 92% (12 to 1 bird) in relative abundance (Table 14). The Golden-winged Warbler is a colonial species and requires a mosaic of seral stages for breeding, including patches of herbaceous cover, shrub thickets, and a forested edge (Klaus and Buehler 2000, Rossell 2001, Rossell et. al. 2002). As a result of impacts of stream restoration, beaver activity, and natural succession, much of the habitat favored by Golden-winged Warblers at Tulula has been modified or lost. The number of Golden-winged Warbler territories has decreased from 12-14 territories in 1998 to 3-4 territories in 2006. In 2006, Golden-winged Warbler territories were only located in more upland areas, where conditions were drier and where a mosaic of habitat types still occurred.

Table 14. Relative abundance and migratory status of birds recorded during breeding bird surveys in 32, 82-ft radius plots during 1994, 1998, 2000, 2002, 2004, and 2006.

	1994	1998	2000	2002	2004	2006	Migratory
Species			Number				Status
Acadian Flycatcher	2	8	1	1	3	9	N
American Goldfinch	0	5	3	2	2	2	Y
American Robin	0	1	0	3	0	1	D
Belted Kingfisher	0	0	0	0	0	1	Y
Blue-gray Gnatcatcher	5	3	4	8	4	3	N
Blue-headed Vireo	0	0	0	1	0	0	N
Brown-headed Cowbird	0	0	0	1	0	0	D
Brown Thrasher	1	0	0	1	0	0	D
Black-and-White Warbler	1	1	0	0	3	3	N
Blue Jay	0	1	0	0	0	2	Y
Carolina Chickadee	7	1	2	6	5	8	Y
Carolina Wren	0	3	0	1	5	2	Y
Common Grackle	0	0	0	0	1	0	Y
Common Yellowthroat	6	0	0	1	2	2	N
Chestnut-sided Warbler	6	1	1	8	2	0	N
Cedar Waxwing	4	10	1	9	0	0	D
Downy Woodpecker	2	1	1	1	2	1	Y
Eastern Pewee	0	0	0	0	1	0	N
Eastern Phoebe	0	0	0	1	0	0	D
Golden-winged Warbler	12	11	4	0	1	1	N
Gray Catbird	2	0	0	0	0	1	Y
Hermit Thrush	0	0	0	0	0	1	N
Hooded Warbler	5	14	5	7	2	9	N
Indigo Bunting	28	22	4	7	5	3	N
Kentucky Warbler	6	5	5	1	7	1	N
Mourning Dove	0	1	0	0	0	0	Y
Northern Bobwhite Quail	0	0	0	3	1	0	Y
Northern Cardinal	4	1	3	7	2	6	Y

Northern Flicker	1	0	0	0	0	0	Y
Northern Parula	8	12	4	15	6	4	N
N. Rough-winged Swallow	0	2	0	4	0	0	N
Ovenbird	2	3	1	5	0	2	N
Palm Warbler	0	0	0	0	0	1	N
Pileated Woodpecker	0	1	1	1	1	0	Y
Red-eyed Vireo	8	14	16	18	6	9	N
Ruby-throated Hummingbird	0	4	3	4	1	1	N
Rufous-sided Towhee	7	7	5	12	9	4	Y
Red-winged Blackbird	0	0	0	10	3	10	D
Scarlet Tanager	0	1	1	0	0	1	N
Song Sparrow	1	7	5	11	6	6	Y
Swainson's Warbler	0	2	0	0	0	0	N
Tufted Titmouse	1	3	3	6	5	3	Y
White-breasted Nuthatch	1	0	0	0	1	0	Y
White-eyed Vireo	7	14	8	12	2	3	N
Wood Duck	0	0	0	0	0	1	D
Wood Thrush	0	0	0	2	1	0	N
Yellow-breasted Chat	9	10	7	4	0	0	N
Yellow-throated Vireo	2	1	1	1	0	1	N
Yellow-throated Warbler	3	3	0	2	0	0	N
Total Species	28	33	24	33	29	32	
Total Individuals	144	174	89	175	90	103	

Note: Migratory status from Hamel (1992).
N = Neotropical migrant, D = Short-distance migrant, Y = Year-round resident.

DISCUSSION

Tulula continues to change in response to restoration and as natural processes respond to changing site conditions. We have developed a fairly comprehensive understanding of annual and seasonal variability in the structural and functional attributes of this restoration project.

The overall pattern of the restored stream channel has not changed since water was released in the first restored section in September 2001. We have noticed isolated areas of bank and bed erosion, but the channel is performing remarkably well after four years of water flow. Most of the notable areas of bank erosion are associated with beaver dams at the lower end of the site in the past year. Banks have eroded behind the dams and at the point of water entry back into the restored channel. After four years of water flow, bankfull widths did not change. However, we anticipate an increase in erosion problems during subsequent channel surveys in the middle and the lower end of the site due to beaver activity. Most of the channel has degraded to some extent, as noted by increasing cross-sectional areas of riffles and pools.

Changes in site hydrology were noted through the network of manual and electronic wells. The data from manual wells provide a more comprehensive understanding of changes in hydrology. Differences that suggest an improvement in hydrology (rise in water table depth) were observed with manual wells located in the floodplain close to the restored channel. Restoration of Tulula Creek had a minimal effect on the hydrology of the fen. The assessment of site hydrology has been compromised from overbanking of water from beaver dams at the lower end of the site.

Restoration of the Tulula floodplain involved substantial earth moving and disturbance of the soil profile. For tag alder, which is a long-lived nitrogen-fixing shrub, time elapsed since disturbance had obvious implications for its growth and establishment (e.g., longer time since disturbance = older, larger plants with greater sexual and asexual reproductive success). Soil disturbance during restoration resulted in lower levels of soil carbon and nitrogen in an area with a low water table. Alders in this area showed lower sexual and asexual reproductive success. Wet soils appeared to favor the establishment of a large number of tag alders, although the basal diameter of these plants was smaller than that of plants growing in less-crowded, drier soils.
Herbivore damage was more pronounced on tag alder leaves from wet soils, although leaf damage was not correlated with levels of leaf carbon or nitrogen. Sap-feeding insect herbivores were noted in both wet and dry areas, with little difference noted in the levels of infestation. Survival of red maple saplings that were planted in 1995 continued to decline in open areas of the site, while naturally-regenerating saplings continued to flourish in the same areas.

We found that the least disturbed plant communities (particularly red maple) had the quickest decomposition, the greatest amount of litter microarthropods, the most soil organic carbon, and the lowest soil pH. We conclude that soil characteristics related to low disturbance, rather than the presence of a closed canopy, probably have the greatest influence on speed of decomposition and numbers of litter microarthropods. Therefore, the most intact ecosystems appear to be functioning at the healthiest levels.

Researchers have rarely conducted long-term studies of vertebrates to determine changes in community assemblages, or to document population resilience and viability following the creation of breeding habitats at restoration sites. This information is critical for setting realistic time frames and criteria for assessing restoration success. Our project is yielding important information concerning the long-term dynamics of restored wetlands and the response of resident amphibians to environmental perturbations. The data will be useful in designing more meaningful assessment criteria for future restoration projects throughout the eastern U.S.

To enhance population resilience, we used a metapopulation design that involved the creation of a large array of breeding sites that differed in size, depth, and hydroperiod. Many ponds were unproductive in certain years because of premature drying associated with drought, the outbreak of a deadly viral disease, and the invasion of ponds by fish due to beaver activity and site reconstruction. Despite catastrophic mortality in most ponds each year, a few ponds have produced juveniles annually, and total juvenile output has been sufficient to maintain viable adult populations of resident species. The data to date indicate the wetland design at Tulula has resulted in populations that are resilient to major site perturbations associated with drought, disease, and predators.

The substantial changes (pre- vs. post-restoration) observed in the overall species composition and the decrease in relative abundance of birds at Tulula are attributed primarily to the loss of early successional habitats due to flooding by beaver and natural succession. Areas inundated with water (approximately one-third of the floodplain) and areas dominated by single-aged stands of saplings reduce the habitat productivity of birds, by decreasing the coverage of the herbaceous and shrub layers, thereby reducing the diversity of the habitat structure and amount of edge. Overall, generalist species and species associated with water such as the Song Sparrow, Tufted Titmouse, and Red-winged Blackbird have become more abundant, while species associated with early-successional habitats, including many neotropical migrants of conservation concern such as the Golden-winged Warbler, Hooded Warbler, Kentucky Warbler, Swainson's Warbler, White-eyed Vireo, and Yellow-breasted Chat, have become less abundant.

Tulula is the first wetlands mitigation bank in the Blue Ridge Province of North Carolina. Many mitigation banks in North Carolina are located in the Coastal Plain, and are considerably different from Tulula in terms of their hydrology and ecology. Our database on hydrology, soils, flora, and fauna continues to provide a framework for documenting the success of restoration at Tulula. These data were important in the development and design of restoration strategies, and have influenced considerations for site management. Tulula has provided research experience to 70 undergraduates at UNCA, including numerous senior research projects.

RECOMMENDATIONS

1. Beaver dams are exerting a localized but significant impact on bank erosion of the restored channel and are influencing the water table of nearby wetlands. Evaluating the geomorphology and stability of the restored stream channel and site hydrology will require controlling of beaver activity.

2. Eradicating or controlling beaver activity will also maintain or restore the productivity of the habitat for amphibians and birds by controlling or eliminating flooding in key portions of the site.

3. Future site management of the Tulula site should include efforts to retain portions of the site in an early successional stage (for example, using bush-hogging or burning). This would enhance habitat for small but unique heliophytic plants, such as bog button (Eriocaulon decangulare), and rare plants such as the red Canada lily (Lilium canadense ssp. editorum), as well as for uncommon animals such as the Golden-winged Warbler and other neotropical migrants of conservation concern.

4. Monitoring of floral and faunal communities at Tulula should continue, to document how they respond to the hydrologic changes. Ideally, a long-term monitoring program should be developed to gauge the success of the wetlands restoration over a decade or longer.

5. The site should be monitored for the presence of invasive plant species such as cattail (*Typha*

latifolia), which is present in small numbers in some of the wettest habitats. Although they are native, cattails respond to disturbance, and have the potential to dominate these areas, causing a local decline in species diversity. Had Tulula not been disturbed for a golf course, aggressive species like cattail would be less of a management issue.

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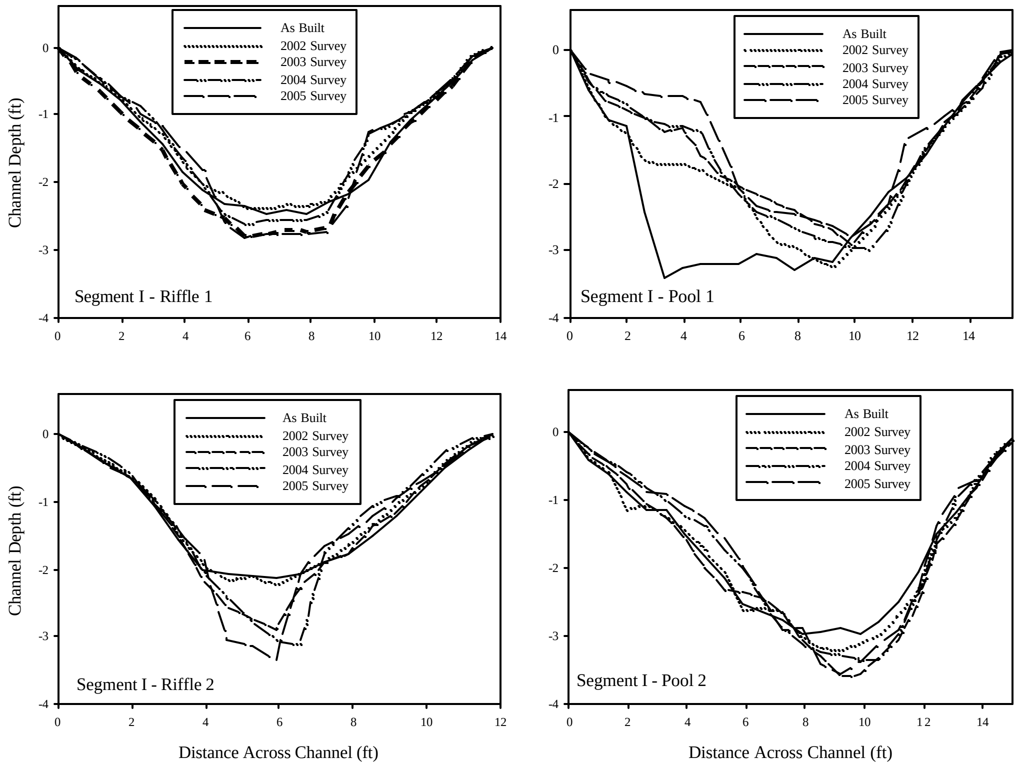
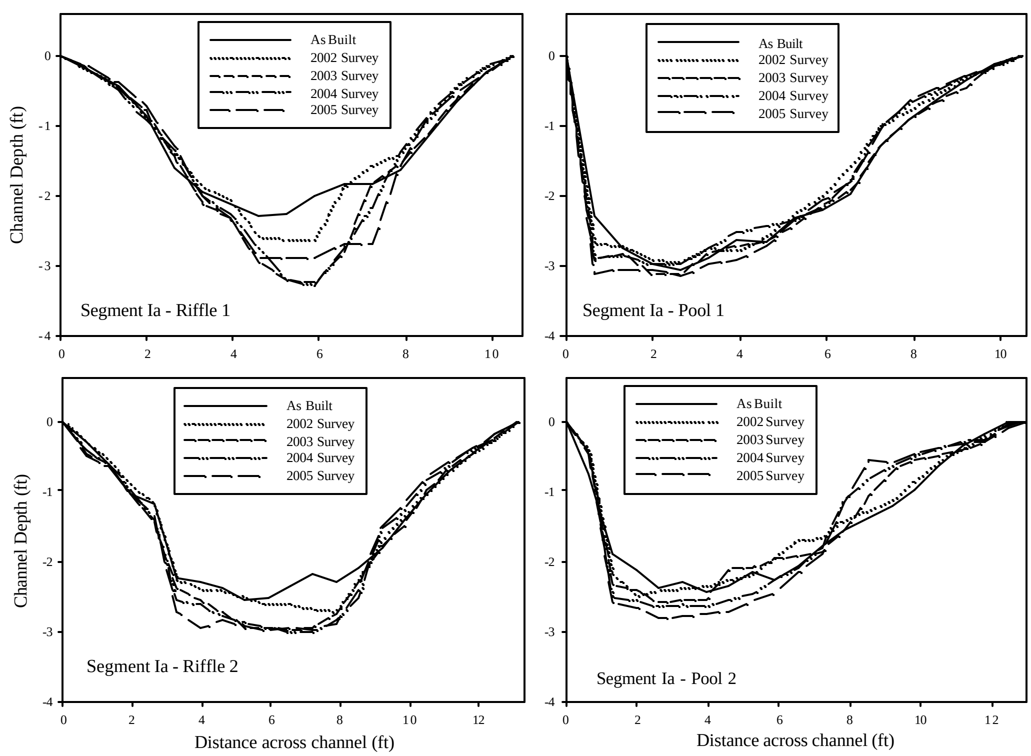
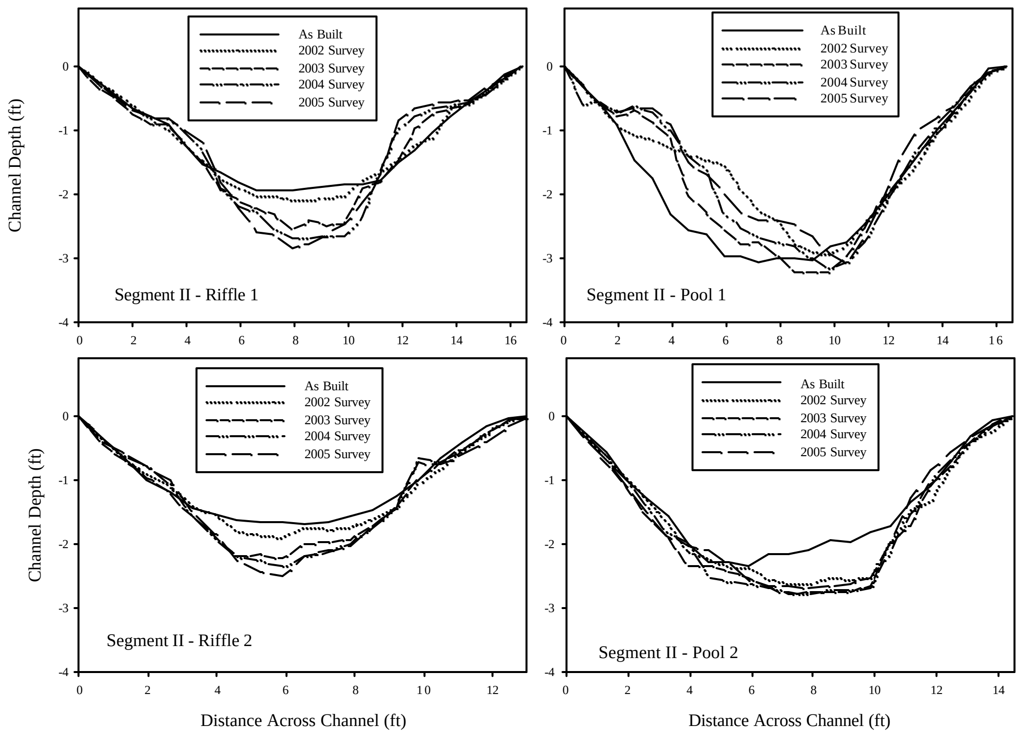
Appendix A1. Cross-sections of riffles and pools in stream segment I.



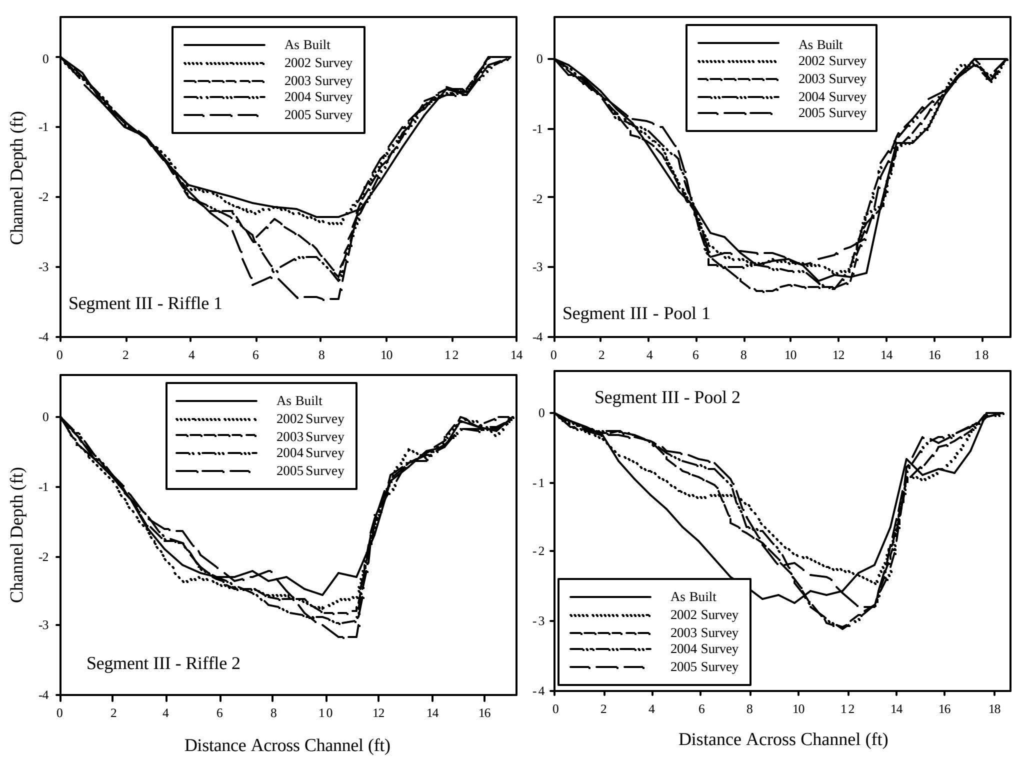
Appendix A2. Cross sections of riffles and pools in stream segment Ia.



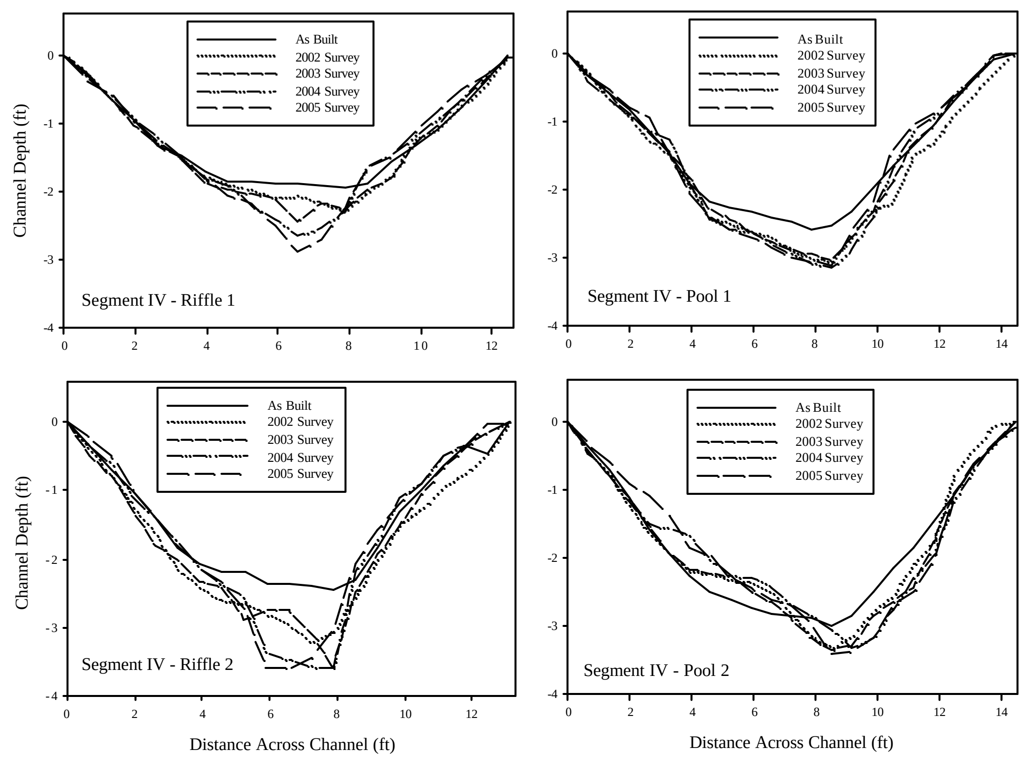
Appendix A3. Cross sections of riffles and pools in stream segment II.



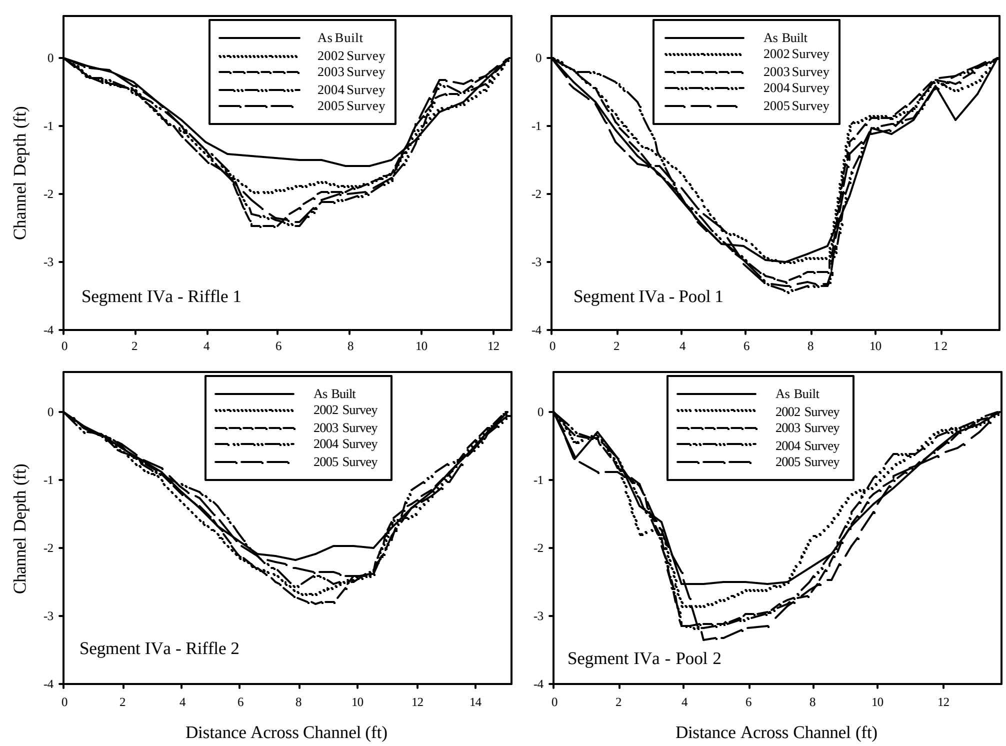
Appendix A4. Cross sections of riffles and pools in stream segment III.



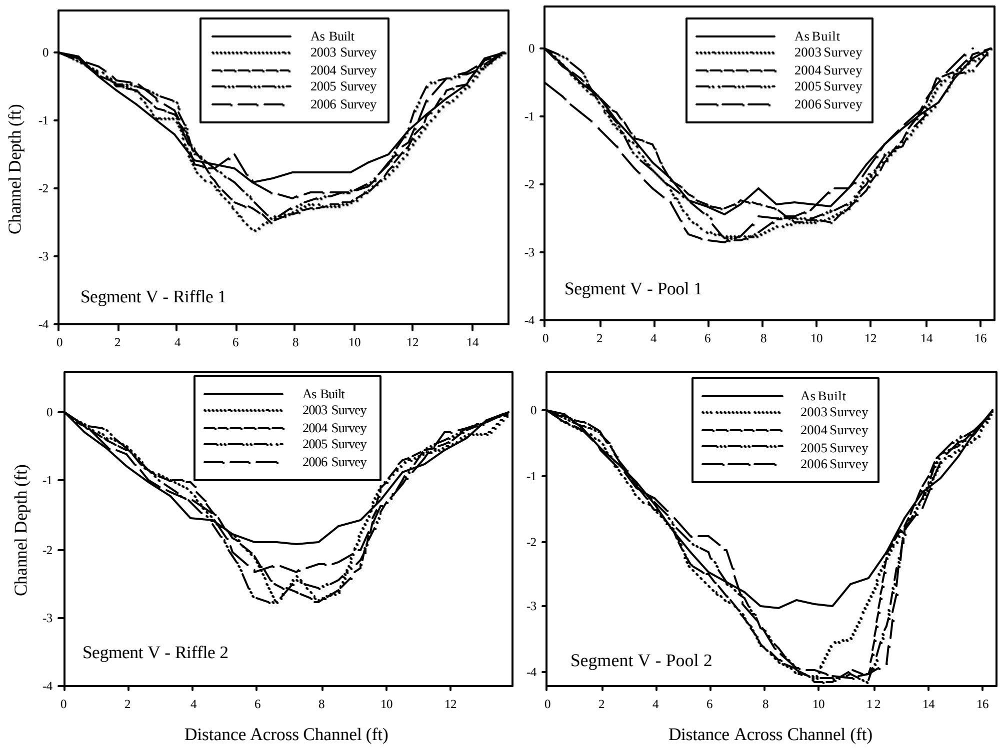
Appendix A5. Cross sections of riffles and pools in stream segment IV.



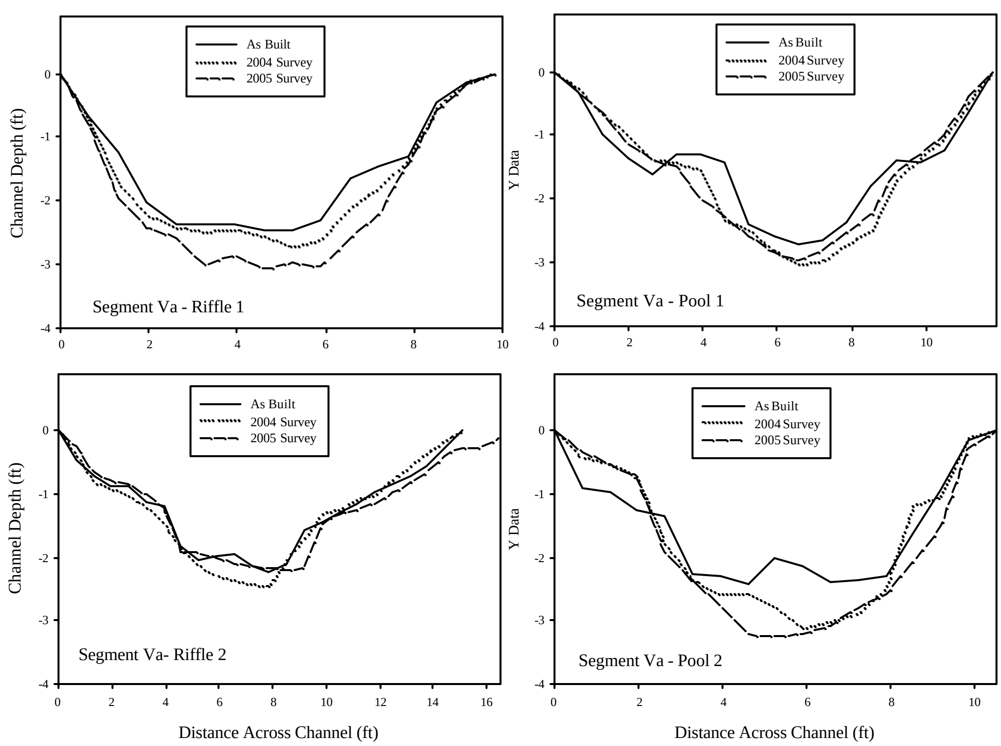
Appendix A6. Cross sections of riffles and pools in stream segment IVa



Appendix A7. Cross sections of riffles and pools in stream segment V.

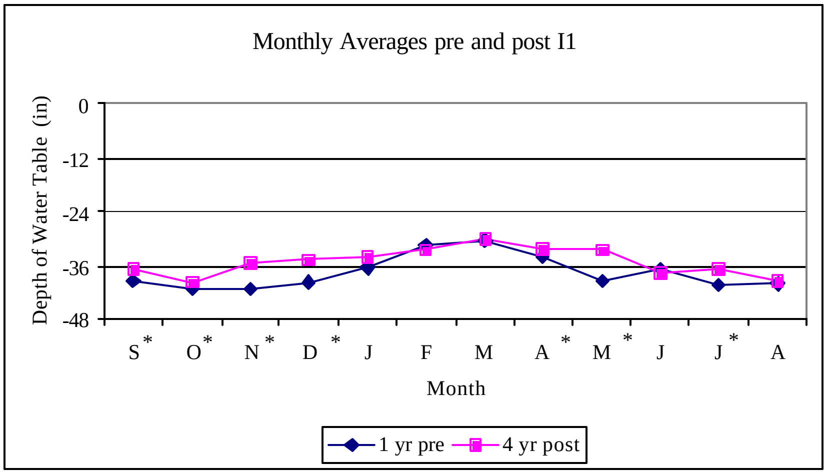


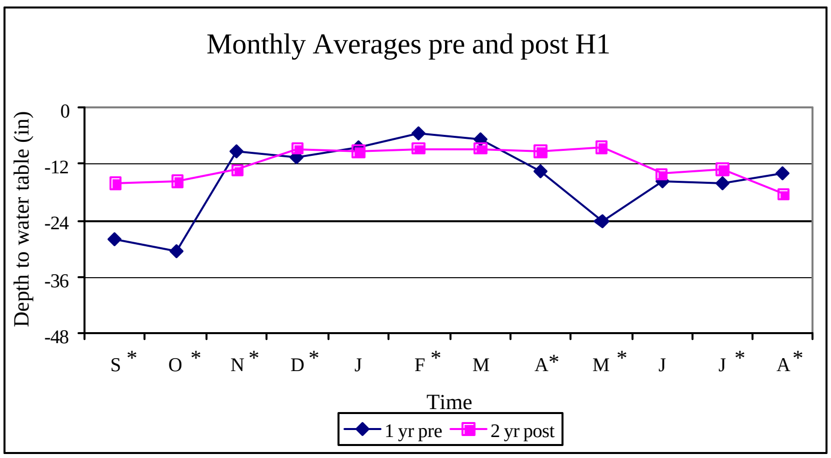
Appendix A8. Cross Sections of riffles and pools in stream segment Va.

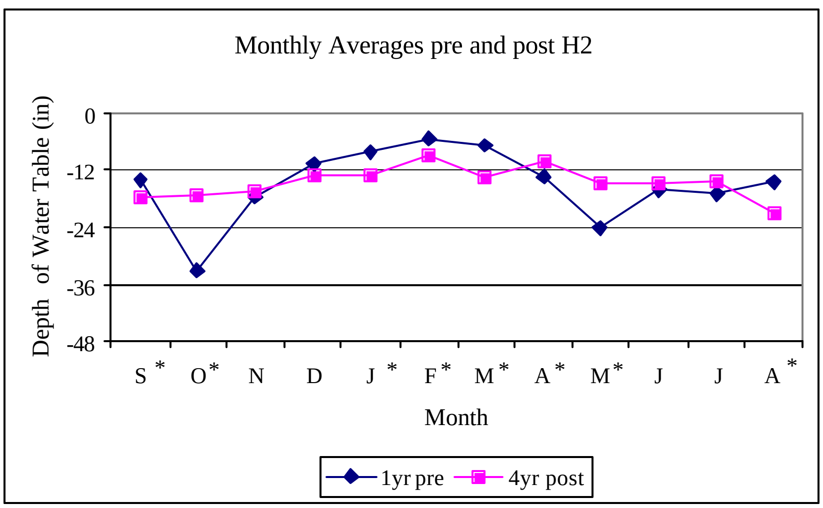


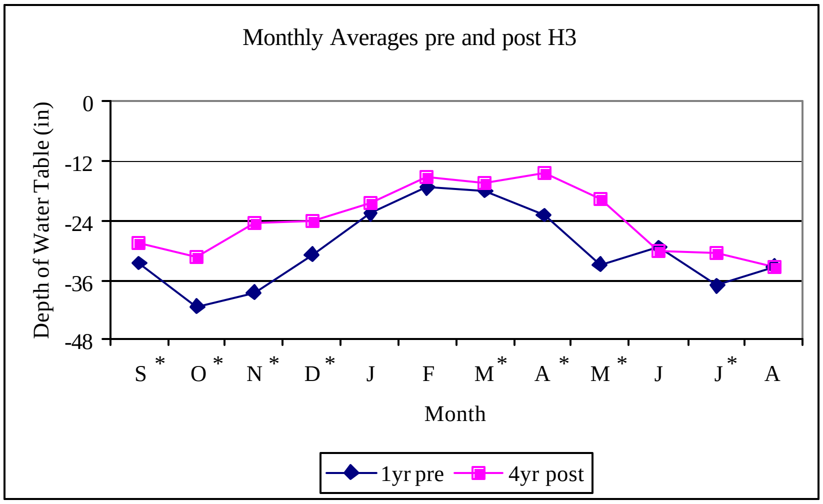
Appendix B. Water-table data for electronic wells (see Fig. 3 for well location). Months with asterisks are significantly different.

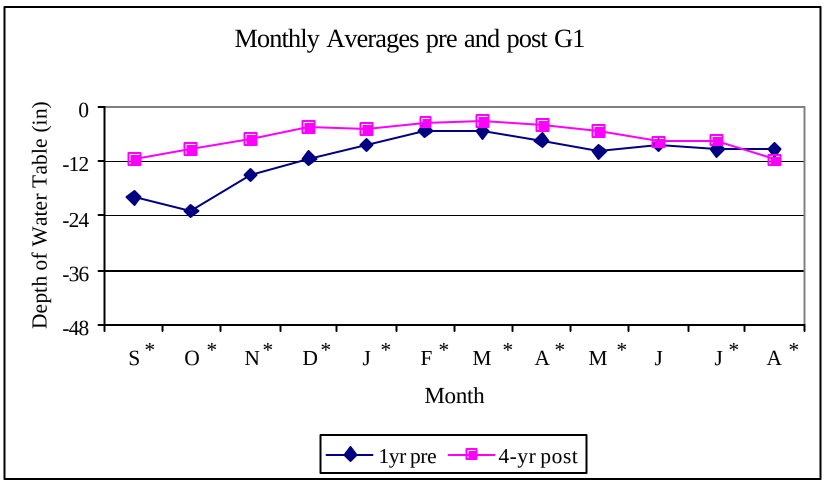
B1. Pre- and post-restoration water-table data from the electronic wells of stream Section I.



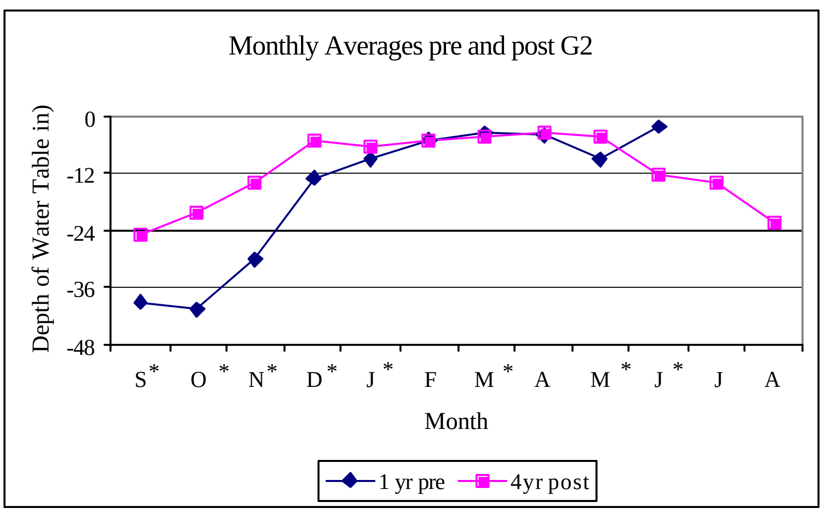


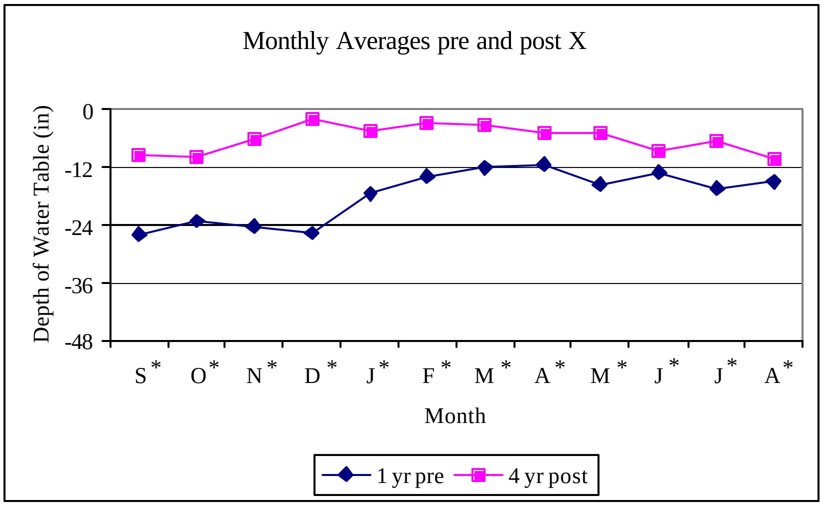






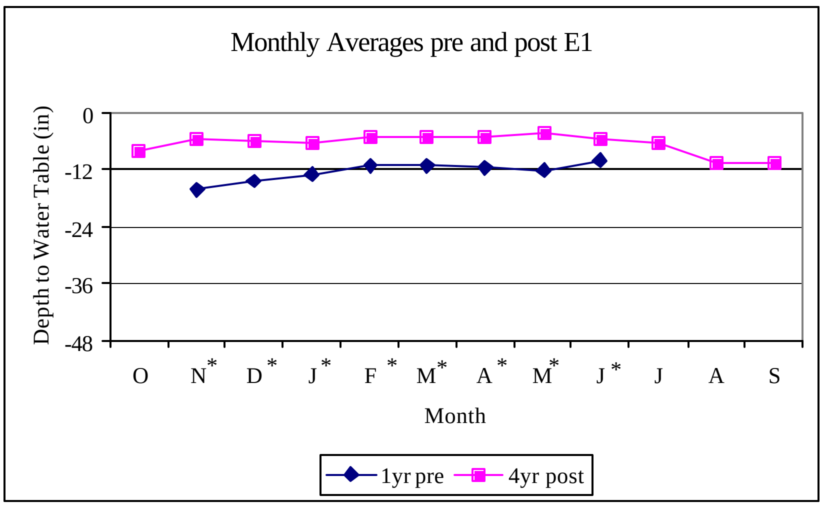
Impacted by dyke



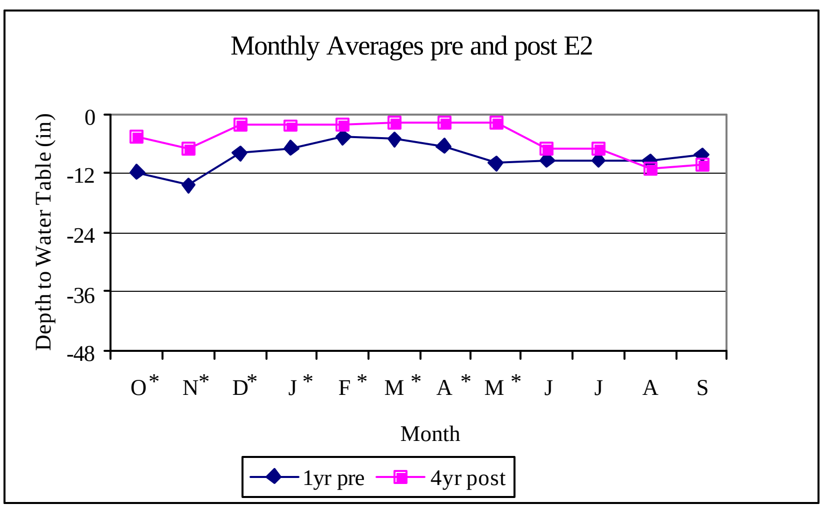


Within 20 ft of channel

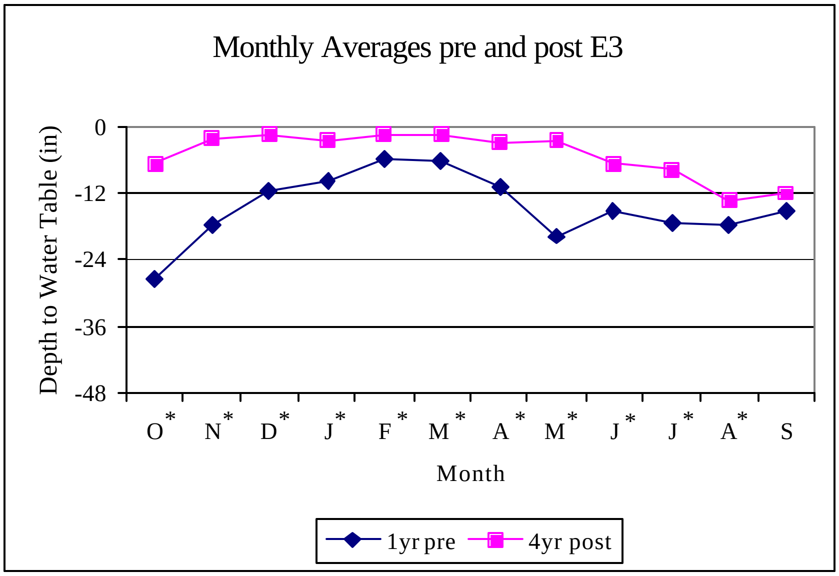
B2. Pre- and post-restoration water-table data from the electronic wells of Section II and III.



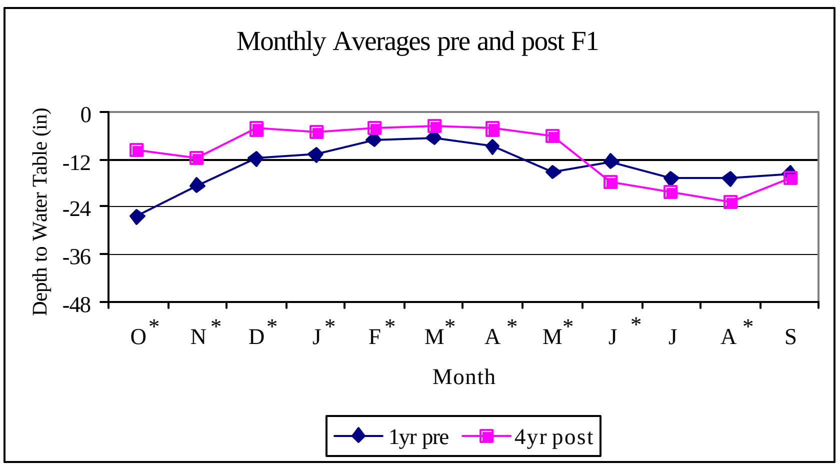
Under large powerline

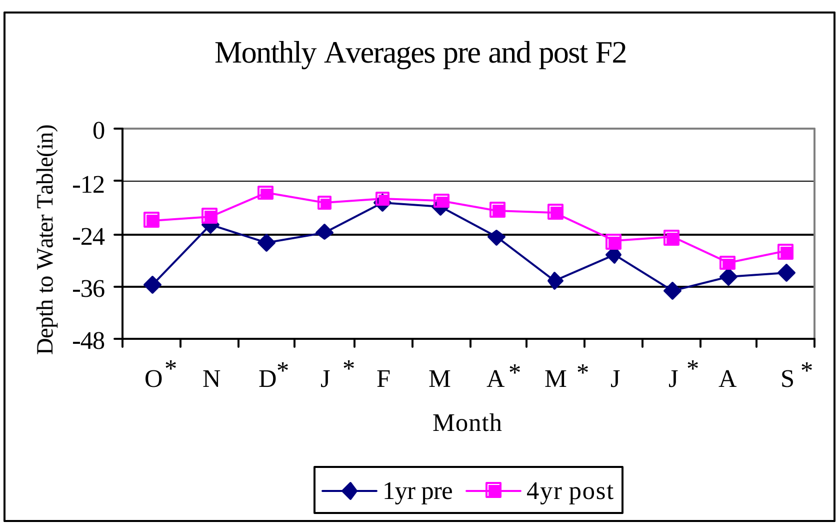


Tulula Fen



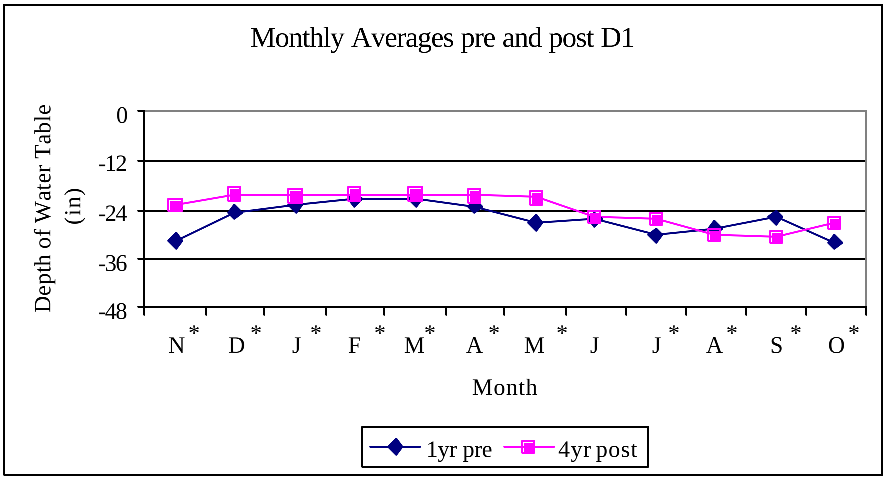
Within 20 ft of channel

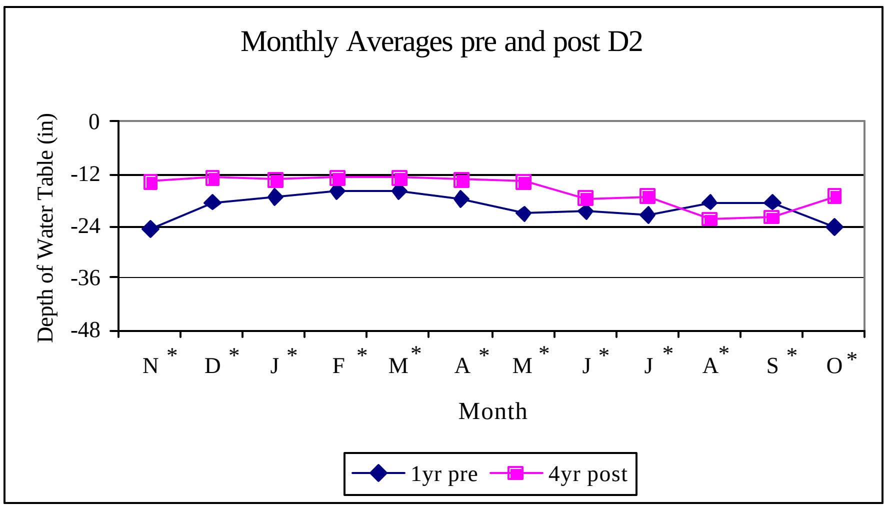




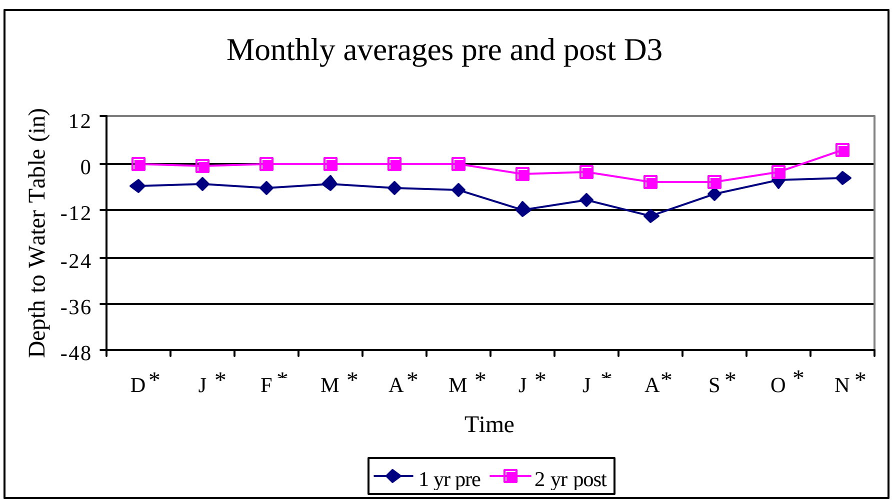
Within 30 ft of channel

B3. Pre- and post-restoration water-table data from the electronic wells of Section IV.



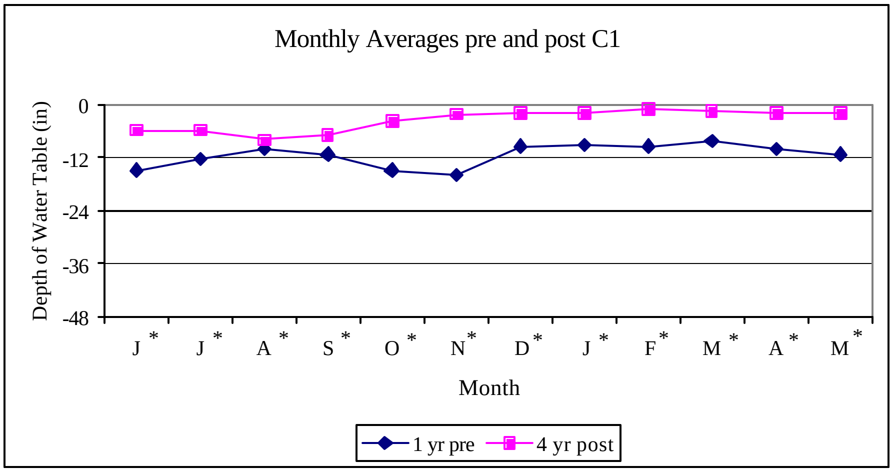


Adjacent to manual well D60

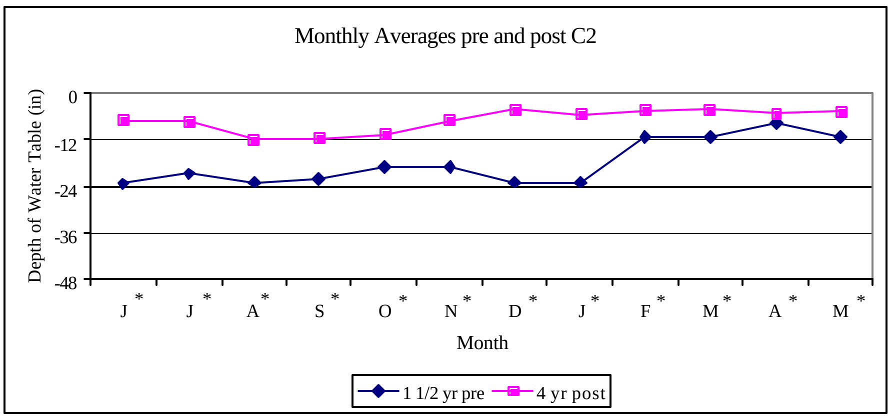


Impacted by beaver

B4. Pre- and post-restoration water-table data from the electronic wells of Section V.

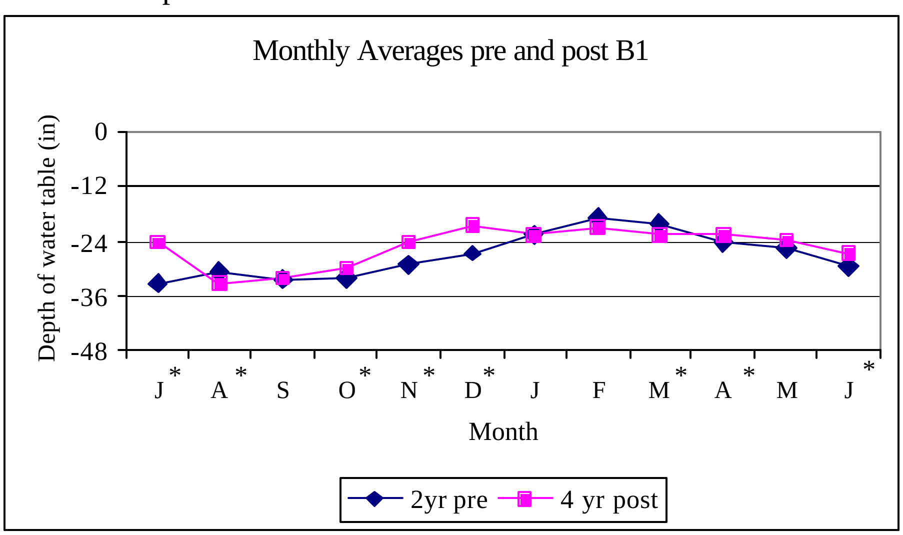


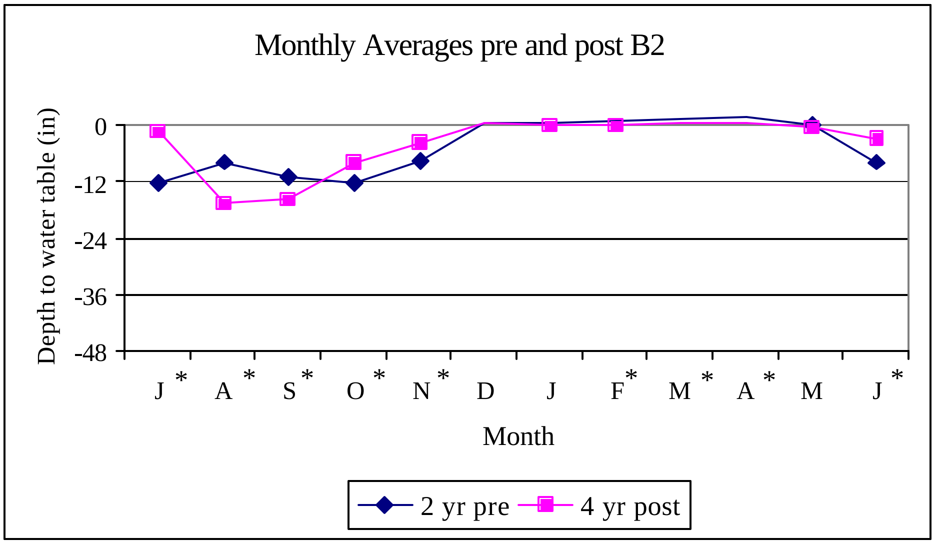
Impacted by beaver



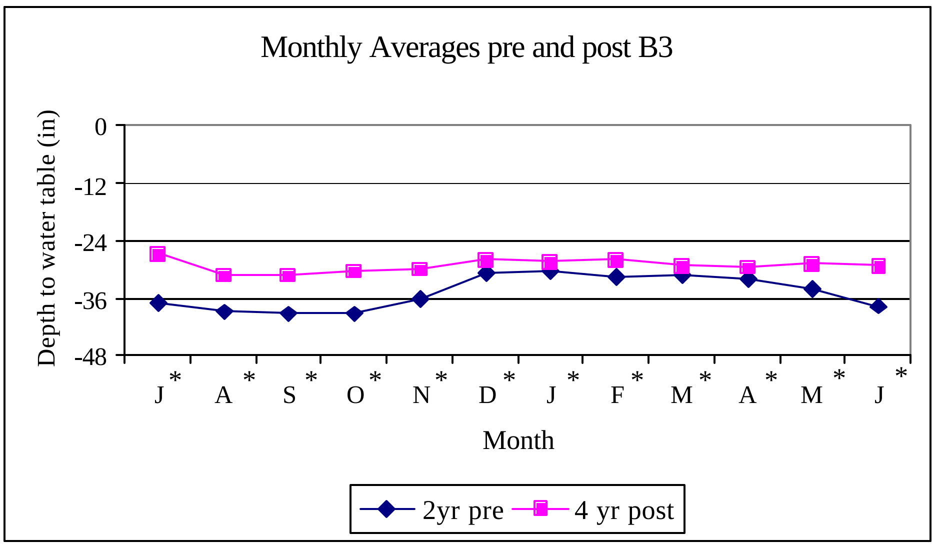
Impacted by beaver

B5. Pre- and post-restoration water-table data from the electronic wells of Section Va.

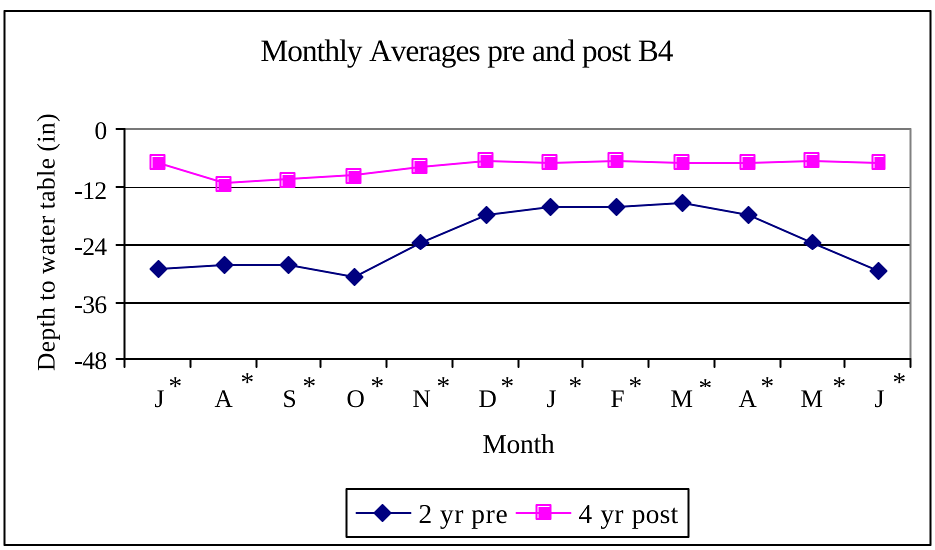




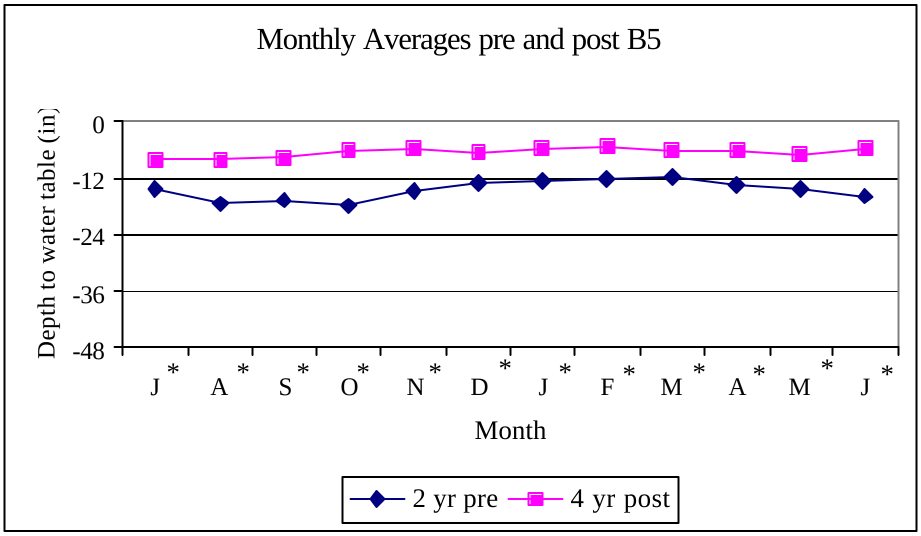
Above old railroad bed



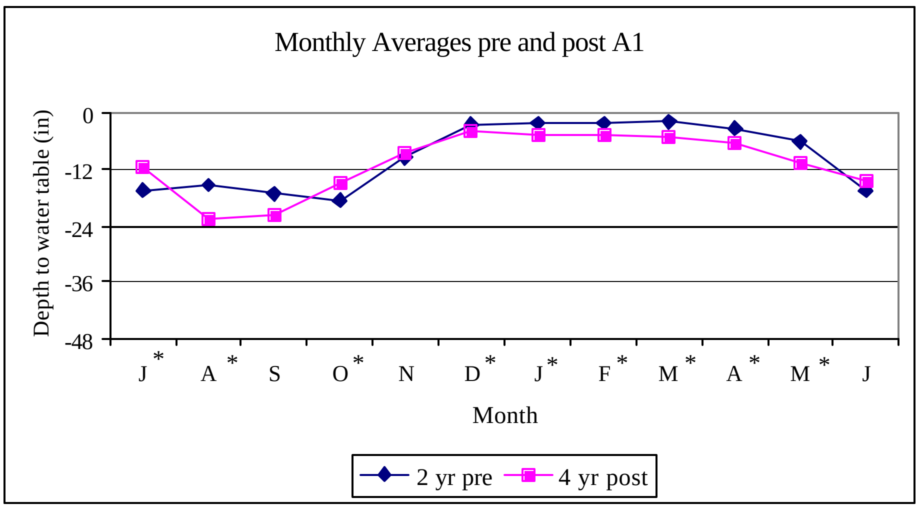
Below old railroad bed



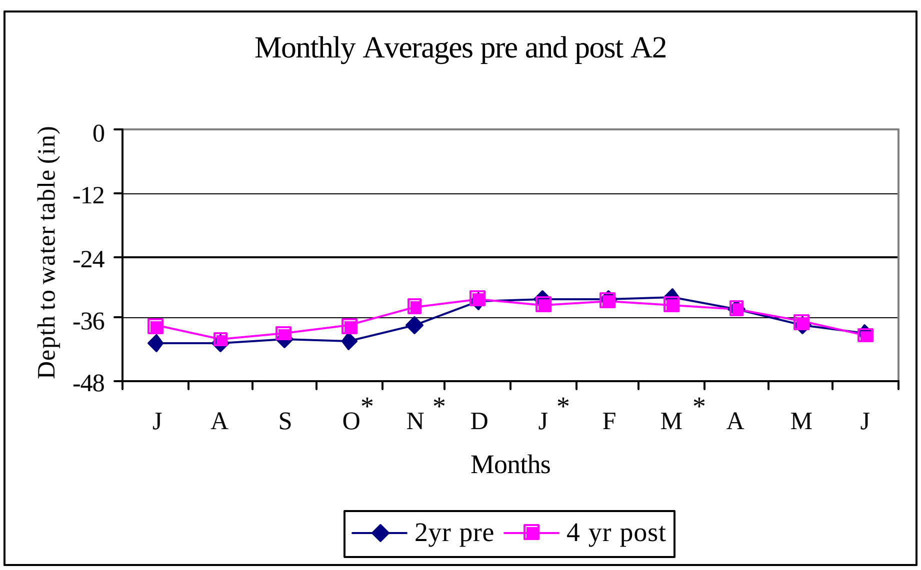
Impacted by beaver



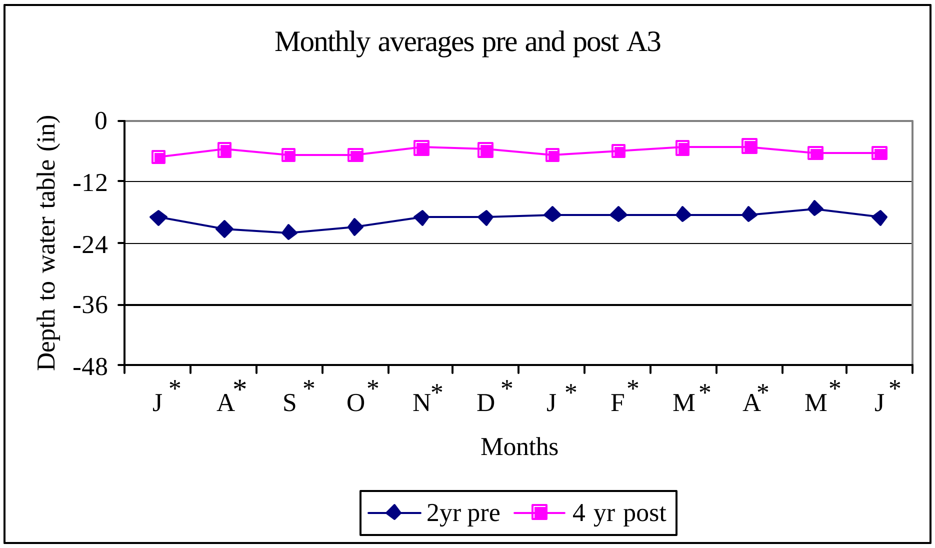
Impacted by beaver



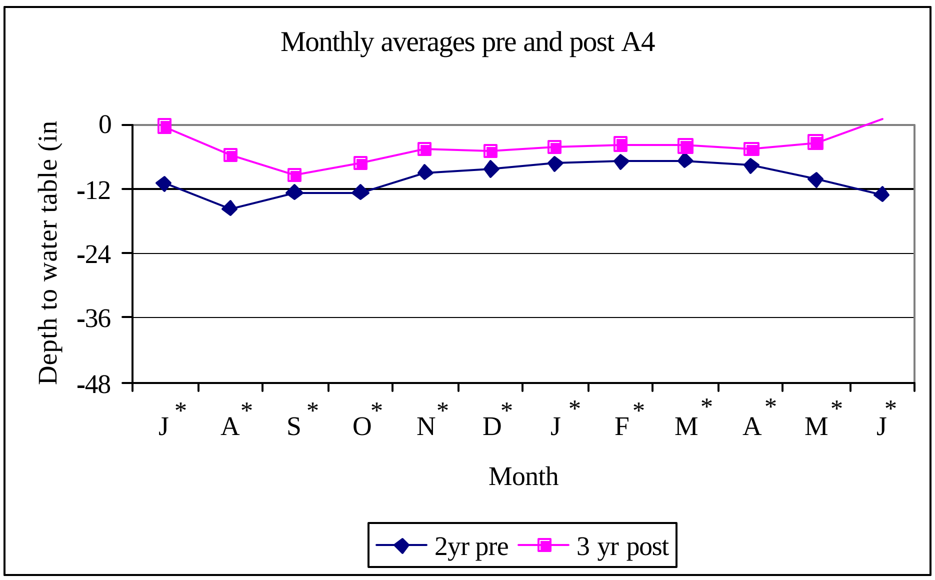
Above old railroad bed



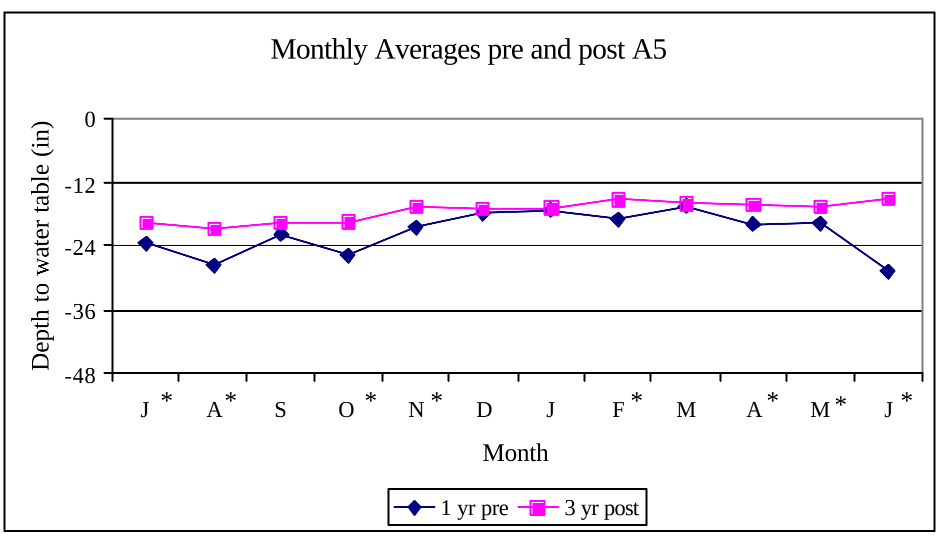
Below old railroad bed



Impacted by beaver



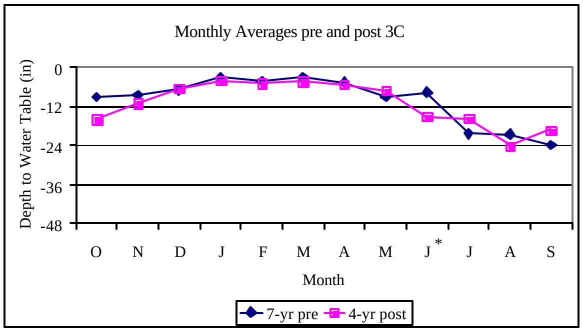
Impacted by beaver

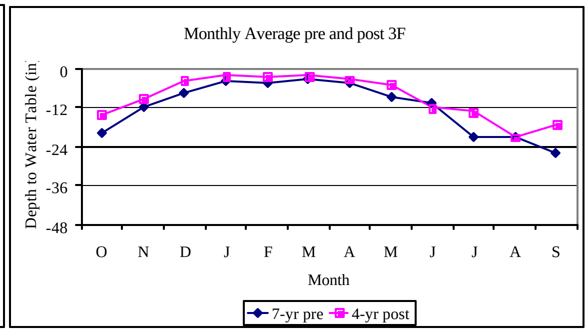


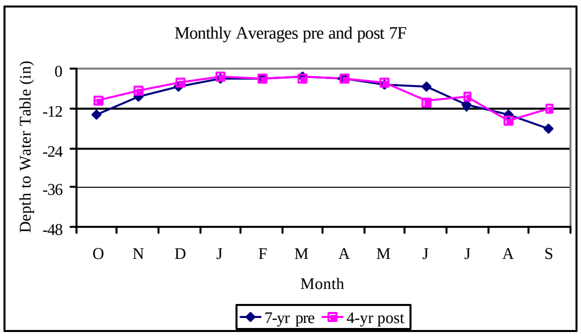
Appendix C. Water-table data from manual wells (see Fig. 3 for location of site location of wells). Months with asterisks are significantly different.

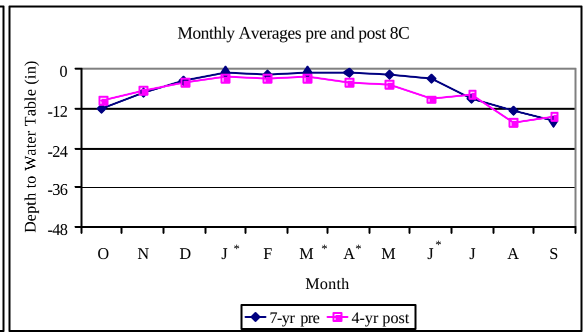
C1. Pre- and post-restoration water table from manual wells located on the eastern side of Tulula.

C1a. Six manual wells in Tulula fen (Stream Section IV).

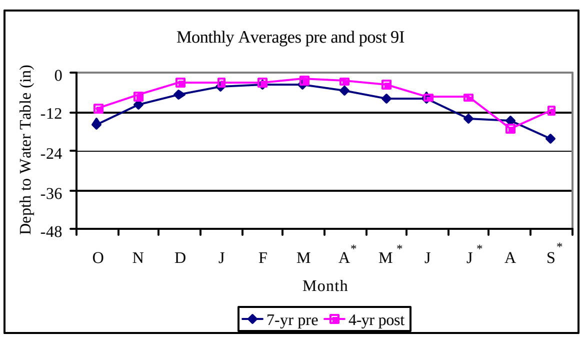


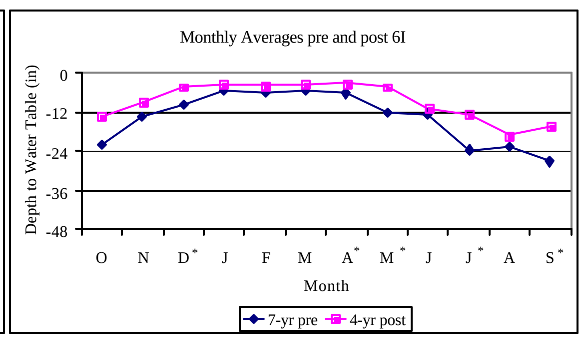




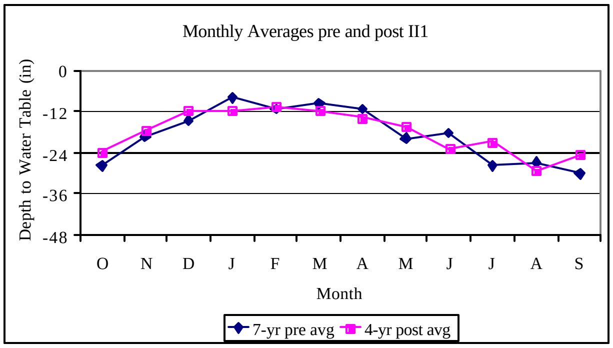


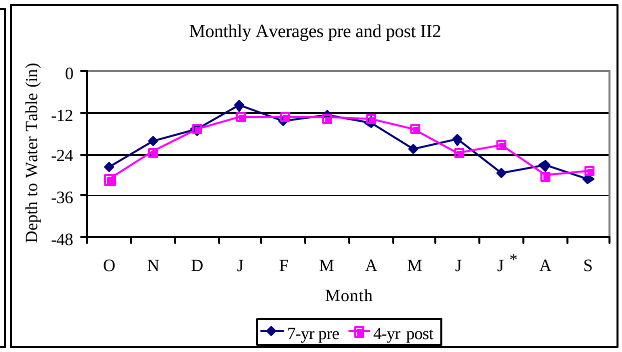
Wells in Tulula Fen closest to restored channel

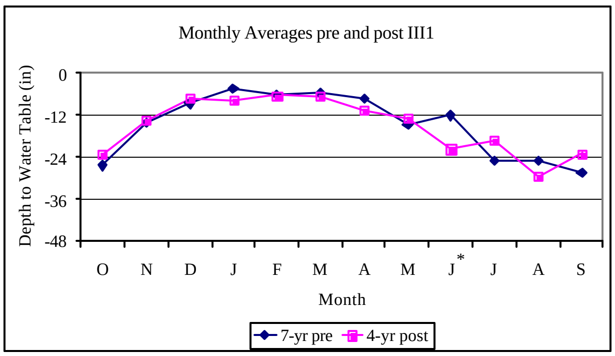


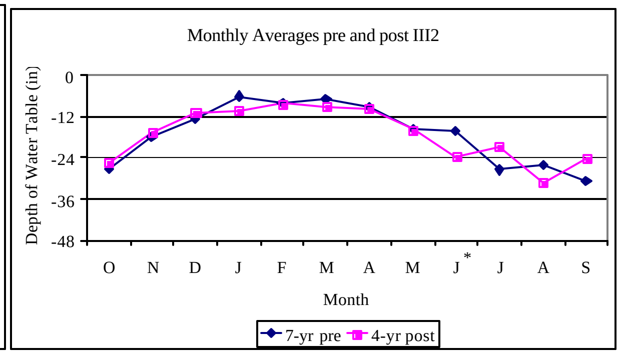


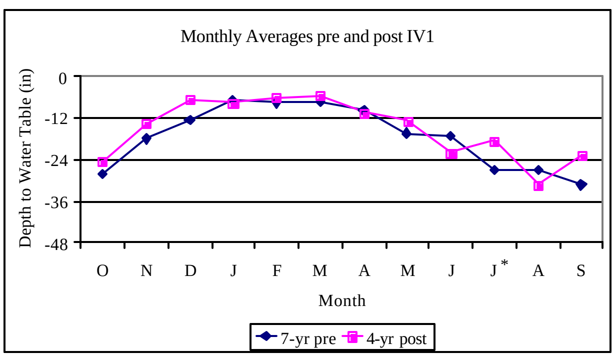
Appendix C1b. Six manual wells located on floodplain east of Tulula fen (Stream Section III).

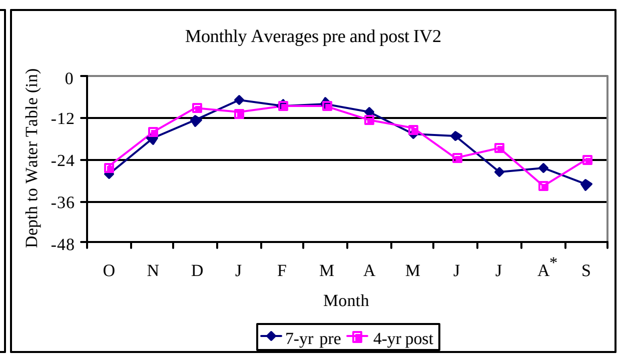




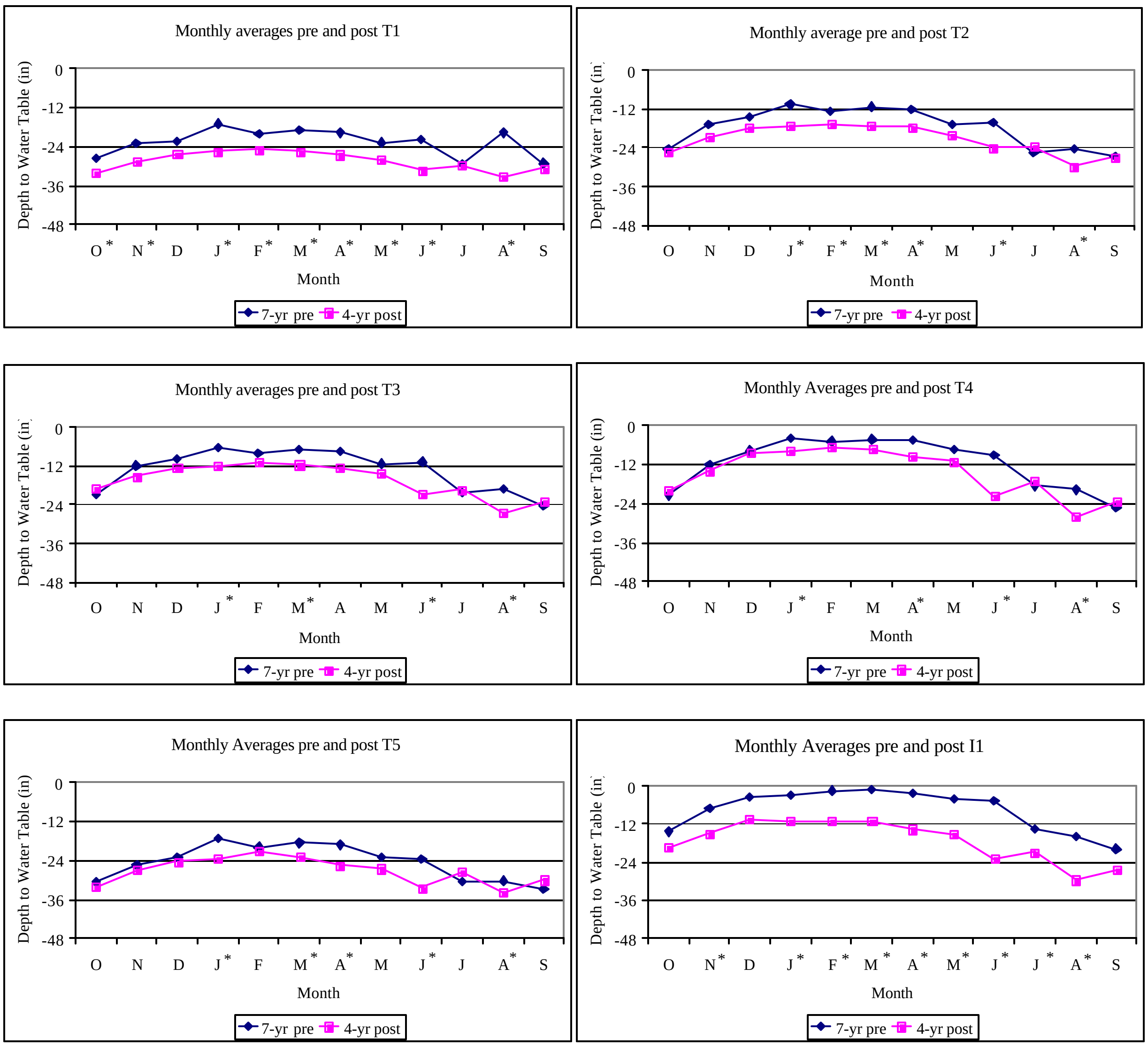






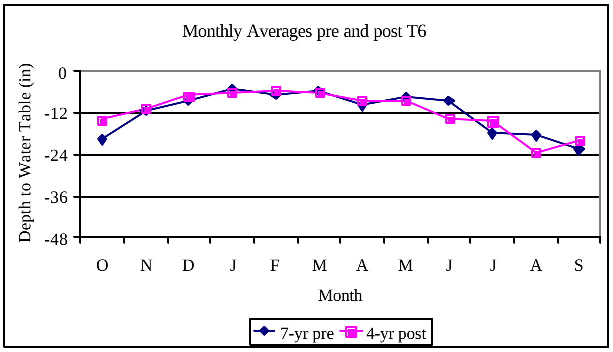


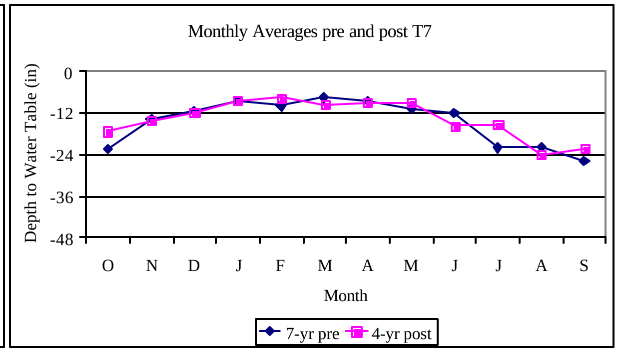
Appendix C1c. Transect wells (T-series) located on hillslope and floodplain west of Tulula Fen (Stream Section IV).

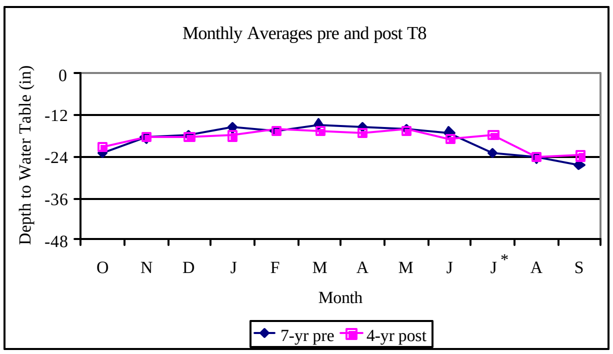


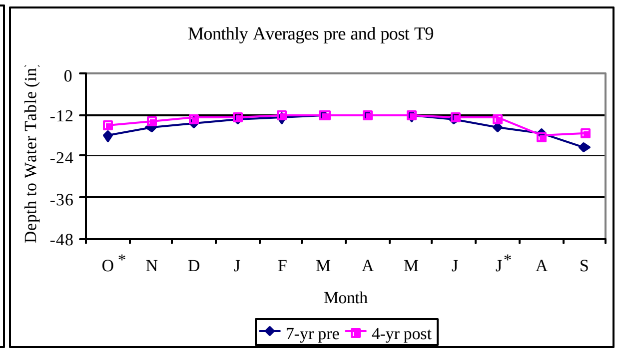
Appendix C1d. Transect wells (T-Series) located on two hillslopes and floodplain north of Tulula Fen (Stream Section IV).

First Transect

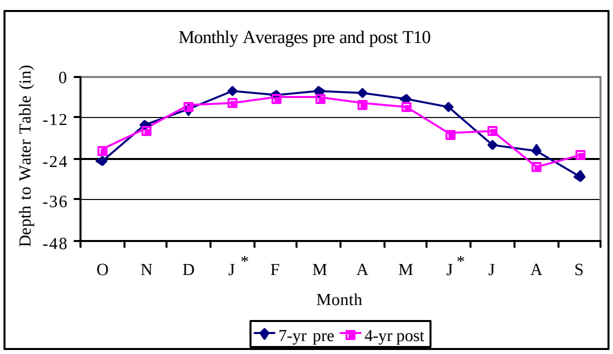


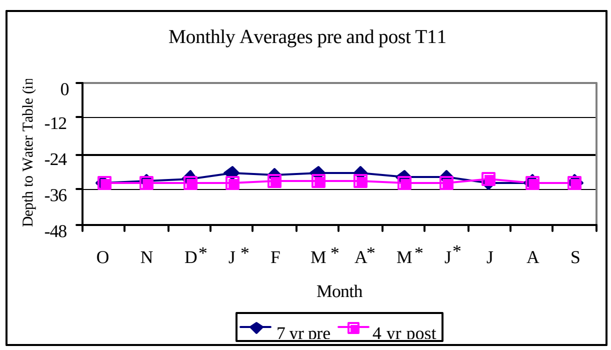




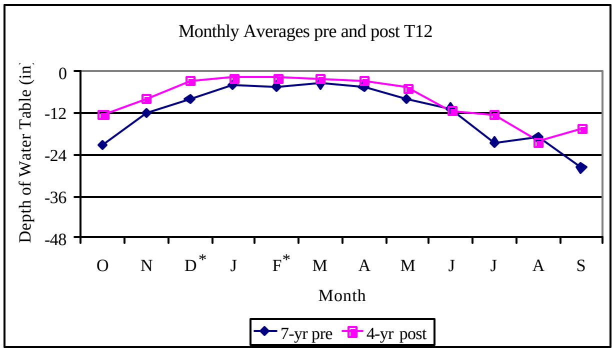


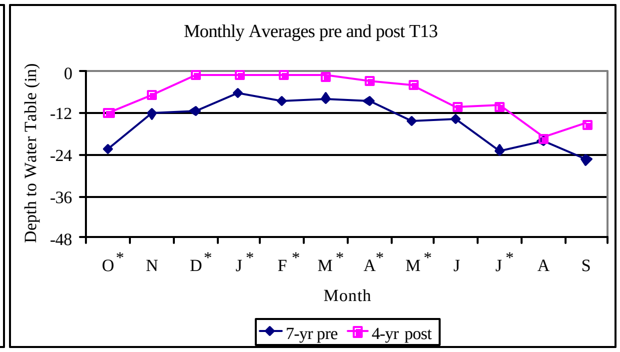
Second Transect

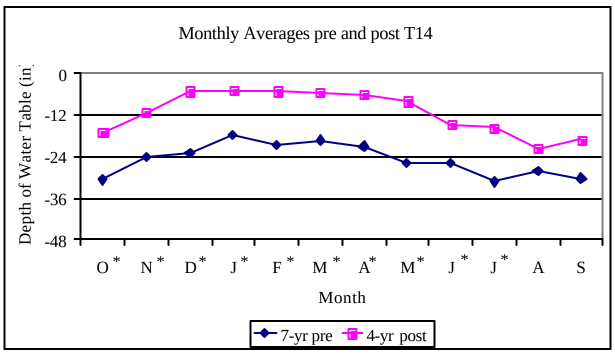




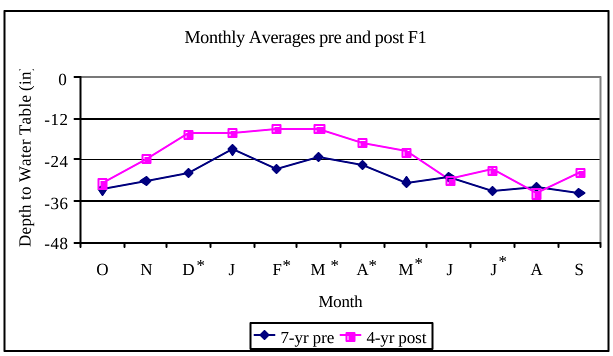
Appendix C1d. Transect wells (T-Series) located between restored Tulula Creek and Tulula Fen (Stream Section IV).



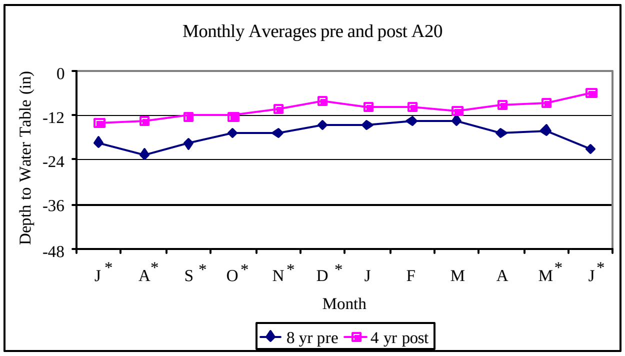


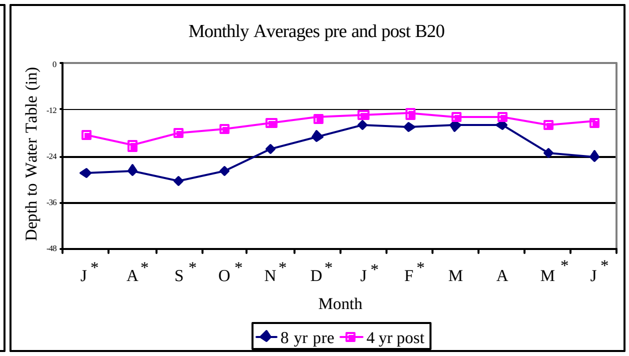


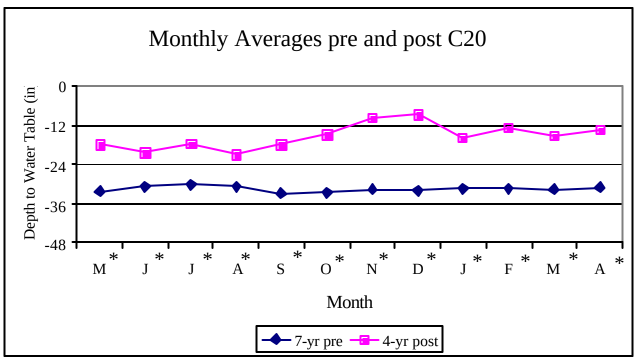
Single well located near restored channel (Stream Section II).



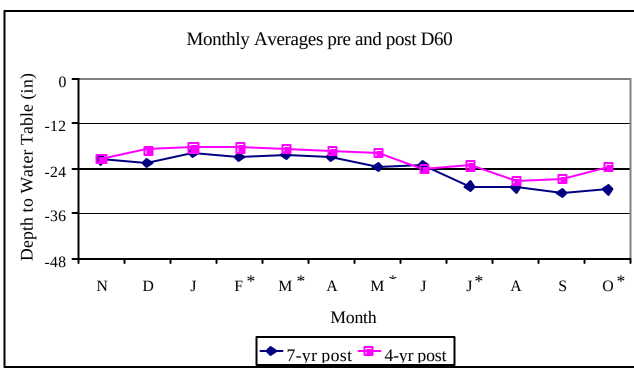
Appendix C1e. Manual wells at lower end of site (Stream Sections V and Va) and impacted by beaver.

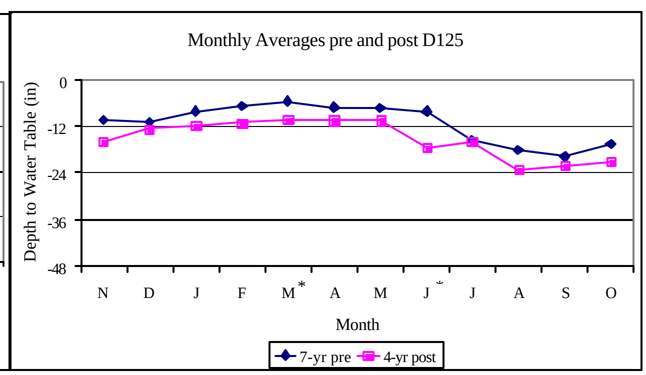




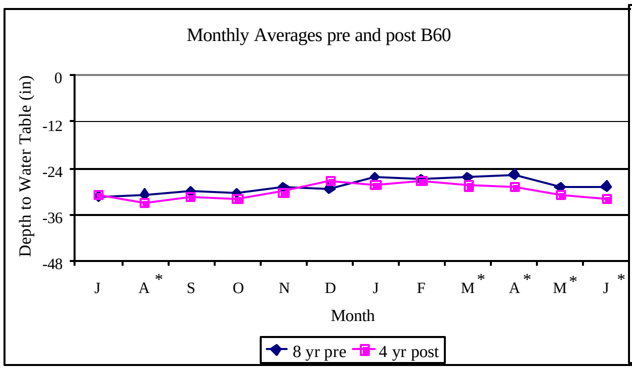


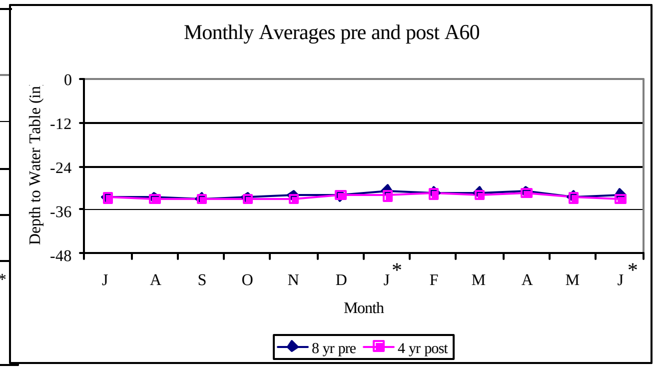
Additional wells located in Stream Section IVa.

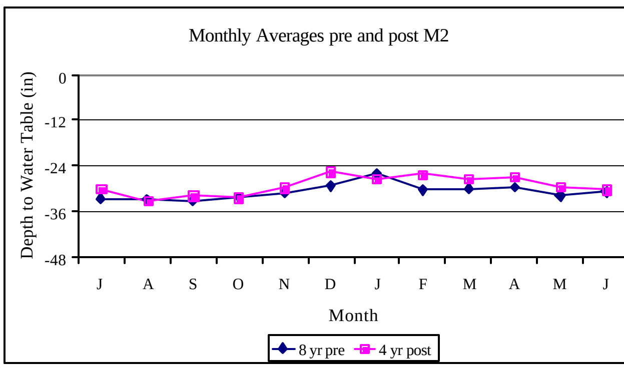


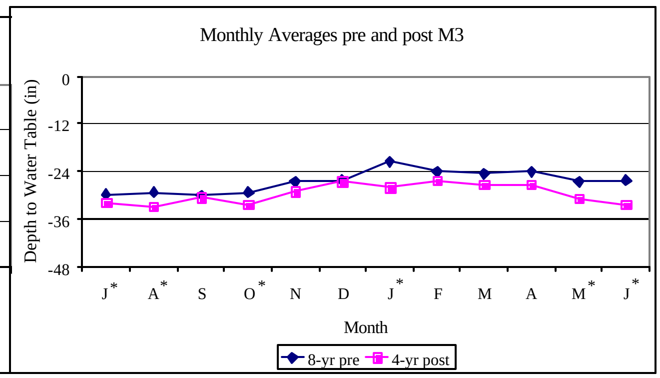


Appendix C1f. Additional manual wells at the lower end of the site (Stream Section Va).









APPENDIX D. Amphibian and Reptile species at Tulula

Common Name	Scientific name
Family Ambystomatidae	
spotted salamander	*Ambystoma maculatum*
Family Plethodontidae	
four-toed salamander	*Hemidactylium scutatum*
Ocoee salamander	*Desmognathus ocoee*
black-bellied salamander	*D. quadramaculatus*
Blue Ridge two-lined salamander	*Eurycea bislineata wilderae (= E. wilderae)*
three-lined salamander	*E. guttolineata*
black-chinned red salamander	*Pseudotriton ruber schencki*
Blue Ridge spring salamander	*Gyrinophilus porphyriticus danielsi*
southern Appalachian salamander	*Plethodon teyahalee*
southern red-backed salamander	*Plethodon serratus*
Family Salamandridae	
red-spotted newt	*Notophthalmus v. viridescens*
Family Bufonidae	
American toad	*Bufo a. americanus*
Family Ranidae	
American bullfrog	*Rana catesbeiana*
green frog	*Rana clamitans melanota*
wood frog	*Rana sylvatica*
Family Hylidae	
northern spring peeper	*Pseudacris c. crucifer*
gray treefrog	*Hyla chrysoscelis*
--	
Family Chelydridae	
common snapping turtle	*Chelydra s. serpentina*
Family Emydidae	
bog turtle	*Clemmys muhlenbergii*
eastern box turtle	*Terrepene c. carolina*
Family Iguanidae (Phyrynosomatidae)	
eastern fence lizard	*Sceloporus u. undulatus*
Family Scincidae	
five-lined skink	*Eumeces fasciatus*
Family Colubridae	
northern water snake	*Nerodia s. sipedon*
eastern garter snake	*Thamnophis s. sirtalis*
eastern ribbon snake	*Thamnophis s. sauritis*
northern ringneck snake	*Diadophis punctatus edwardsii*
black rat snake	*Elaphe o. obsoleta*
northern black racer	*Coluber c. constrictor*
Family Viperidae	
timber rattlesnake	*Crotalus horridus*
northern copperhead	*Agkistrodon contortrix mokasen*

APPENDIX E. Bird Species at Tulula Wetland (1994-2006).

(1) Probably breeding.
(2) Nest found.
(3) Migrant.
(4) Foraging, but not breeding.
(5) Winter resident.

Common Name	Scientific Name
Family Ardeidae (herons and bitterns)	
Great Blue Heron (4)	*Ardea herodias*
Green Heron (4)	*Butorides striatus*
Family Anatidae (waterfowl)	
Wood Duck (4)	*Aix sponsa*
Family Cathartidae (American vultures)	
Black Vulture (4)	*Coragyps atratus*
Turkey Vulture (4)	*Cathartes aura*
Family Accipitridae (hawks)	
Red-tailed Hawk (4)	*Buteo jamaicensis*
Red-shouldered Hawk (4)	*Buteo lineatus*
Broad-winged Hawk (2)	*Buteo platypterus*
Cooper's Hawk (4)	*Accipiter cooperii*
Family Pandionidae (ospreys)	
Osprey (3)	*Pandion haliaetus*
Family Strigidae (typical owls)	
Eastern Screech Owl (4)	*Otus asio*
Barred Owl (4)	*Strix varia*
Great Horned Owl (2)	*Bubo virginianus*
Family Tetraonidae (grouse)	
Ruffed Grouse (4)	*Bonasa umbellus*
Family Phasianidae (quail, pheasants, etc.)	
Northern Bobwhite (1)	*Colinus virginianus*
Family Meleagrididae (turkeys)	
Wild Turkey (2)	*Meleagris gallopavo*
Family Scolopacidae (sandpipers)	
American Woodcock (1)	*Scolopax minor*
Common Snipe (4)	*Capella gallinago*
Solitary Sandpiper (3)	*Tringa solitaria*
Spotted Sandpiper (3)	*Actitis macularia*
Family Columbidae (pigeons and doves)	
Mourning Dove (1)	*Zenaida macroura*
Family Cululidae (cuckoos)	
Yellow-billed Cuckoo (4)	*Coccyzus americanus*
Black-billed Cuckoo (3)	*Coccyzus erythropthalmus*
Family Caprimulgidae (goatsuckers)	
Whip-poor-will (1)	*Caprimulgus vociferus*
Family Apodidae (swifts)	
Chimney Swift (4)	*Chaetura pelagica*
Family Trochilidae (hummingbirds)	
Ruby-throated Hummingbird (2)	*Archilochus colubris*

Family Alcedinidae (kingfishers)

Belted Kingfisher (4) *Ceryle alcyon*

Family Picidae (woodpeckers)

Northern Flicker (2) *Colaptes auratus*
Pileated Woodpecker (4) *Dryocopus pileatus*
Hairy Woodpecker (4) *Picoides villosus*
Downy Woodpecker (1) *Picoides pubescens*

Family Tyrannidae (flycatchers)

Acadian Flycatcher (1) *Empidonax virescens*
Alder Flycatcher (3) *Empidonax alnorum*
Eastern Pewee (1) *Contopus virens*
Eastern Phoebe (1) *Sayornis phoebe*
Eastern Wood-pewee (1) *Contopus virens*

Family Hirundinidae (swallows)

Northern Rough-winged Swallow (4) *Stelgidopteryx serripennis*
Tree Swallow (4) *Tachycineta bicolor*
Barn Swallow (4) *Hirundo rustica*

Family Corvidae (jays and crows)

Blue Jay (1) *Cyanocitta cristata*
Common Raven (4) *Corvus corax*
American Crow (4) *Corvus brachyrhynchos*

Family Paridae (titmice)

Carolina Chickadee (1) *Parus carolinensis*
Tufted Titmouse (1) *Parus bicolor*

Family Sittidae (nuthatches)

White-breasted Nuthatch (1) *Sitta carolinensis*
Red-breasted Nuthatch (3) *Sitta canadensis*

Family Certhiidae (creepers)

Brown Creeper (4) *Certhia americana*

Family Troglodytidae (wrens)

Carolina Wren (1) *Thryothorus ludovicianus*
Winter Wren (3) *Troglodytes troglodytes*

Family Mimidae (mockingbirds, catbirds, thrashers)

Gray Catbird (1) *Dumetella carolinensis*
Brown Thrasher (1) *Toxostoma rufum*

Family Turdidae (thrushes)

American Robin (1) *Turdus migratorius*
Hermit Thrush (3) *Catharus guttatus*
Wood Thrush (1) *Hylocichla mustelina*

Family Sylviidae (kinglets, etc.)

Blue-gray Gnatcatcher (2) *Polioptila caerulea*
Golden-crowned Kinglet (3) *Regulus satrapa*
Ruby-crowned Kinglet (3) *Regulus calendula*

Family Bombycillidae (waxwings)

Cedar Waxwing (1) *Bombycilla cedrorum*

Family Virionidae (vireos)

White-eyed Vireo (1) *Vireo griseus*
Yellow-throated Vireo (1) *Vireo flavifrons*
Solitary Vireo (1) *Vireo solitarius*
Red-eyed Vireo (1) *Vireo olivaceus*

Family Parulidae (wood warblers)

Black-and-white Warbler (1) *Mniotilta varia*
Swainson's Warbler (1) *Limnothlypis swainsonii*

Worm-eating Warbler (3)	*Helmitheros vermivorus*
Golden-winged Warbler (1)	*Vermivora chrysoptera*
Blue-winged Warbler (3)	*Vermivora pinus*
Northern Parula (2)	*Parula americana*
Pine Warbler (1)	*Dendroica pinus*
Black-throated Blue Warbler (3)	*Dendroica caerulescens*
Black-throated Green Warbler (3)	*Dendorica virens*
Yellow-throated Warbler (1)	*Dendroica dominica*
Chestnut-sided Warbler (1)	*Dendroica pensylvania*
Yellow Warbler (3)	*Dendroica petechia*
Ovenbird (2)	*Seiurus aurocapillus*
Kentucky Warbler (2)	*Oporornis formosus*
Common Yellowthroat (1)	*Geothlypis trichas*
Yellow-breasted Chat (1)	*Icteria virens*
Canada Warbler (3)	*Wilsonia canadensis*
Hooded Warbler (2)	*Wilsonia citrina*
American Redstart (3)	*Setophaga ruticilla*
Prairie Warbler (1)	*Dendroica discolor*
Family Icteridae (blackbirds)	
Common Grackle (1)	*Quiscalus quiscula*
Red-winged Blackbird (4)	*Agelaius phoenicus*
Brown-headed Cowbird (1)	*Molothrus ater*
Family Traupidae (tanagers)	
Scarlet Tanager (1)	*Piranga olivacea*
Family Fringillidae (finches, etc.)	
Northern Cardinal (1)	*Cardinalis cardinalis*
Indigo Bunting (2)	*Passerina cyanea*
Blue Grosbeak (3)	*Guiraca caerulea*
American Goldfinch (1)	*Carduelis tristis*
Rufous-sided Towhee (2)	*Pipilo erythrophthalmus*
Northern Junco (5)	*Junco hyemalis*
White-throated Sparrow (5)	*Zonotrichia albicollis*
Field Sparrow (3)	*Spizella pusilla*
Fox Sparrow (3)	*Passerella iliaca*
Swamp Sparrow (5)	*Melospiza georgiana*
Song Sparrow (1)	*Melospiza melodia*

Appendix F. Information Transfer from studies at Tulula.

Publications

Rossell, I.R. 1997. Noteworthy collections from North Carolina: *Lilium canadense* ssp. *editorum*. Castanea 61:196-197.

Moorhead, K.K. and I.M. Rossell. 1997. Southern mountain fens. Pages 379-403 in: Southern forested wetlands: ecology and management. Lewis Publishers, NY. 616 pp.

Petranka, J.W., A.W. Rushlow and M.E. Hopey. 1998. Predation by tadpoles of *Rana sylvatica* on embryos of *Ambystoma maculatum*: Implications of ecological role reversals by *Rana* (predator) and *Ambystoma* (prey). Herpetologica 54:1-13.

Petranka, J. W. and L. J. Hayes. 1998. Chemically mediated avoidance of a predatory odonate (*Anax junius*) by American toad (*Bufo americanus*) and wood frog (*Rana sylvatica*) tadpoles. Behavioural Ecology and Sociobiology 42:2262-2271.

Rossell, C. R., Jr., I. M. Rossell, J. W. Petranka, and K. K. Moorhead. 1999. Characteristics of a partially disturbed southern Appalachian forest-gap bog complex. The Virginia Museum of Natural History, Special Publication No. 7.

Rossell, C. R., Jr. and I. M. Rossell. 1999. Microhabitat selection by small mammals in a southern Appalachian fen in the USA. Wetlands Ecology and Management 7:219-224.

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Petranka, J. W. and C. A. Kennedy. 1999. Pond tadpoles with generalized morphology: is it time to reconsider their functional roles in aquatic communities? Oecologia 120:621-631.

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Presentations

Rossell, I.M. and K. K. Moorhead. Wetlands restoration project in Graham County. UNCA Faculty Forum. March 1995.

Wells, C.L. A comparison of the seed banks of adjacent disturbed and undisturbed North Carolina wetlands. National Conference on Undergraduate Research, Schenectady, NY. April 1995.

Moorhead, K.K. Hydrology and soils of a southern Appalachian swamp-bog complex. Annual meeting of the Association of Southeastern Biologists. Knoxville, TN. April 1995.

Moorhead, K.K. Restoration of Southern Appalachian swamp-bog complexes. Mountain/Piedmont Wetlands Management Workshop. Elkin, NC. May 1995.

Rossell, C.R., Jr., I.M. Rossell, J.W. Petranka, and K.K. Moorhead. Characteristics of a partially disturbed southern Appalachian forest-gap bog complex. Appalachian Biogeography Symposium. Blacksburg, VA. June 1995.

Rossell, C.R., Jr., and I.M. Rossell. Ecology of a mountain bog. Invited presentation. Elisha Mitchell Audubon Society. January 1996.

Rossell, C.R., Jr. Characteristics of a partially disturbed southern Appalachian forest-gap bog. Natural Science Seminar. Warren Wilson College. February 1996.

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Rossell, I.M., and C.R. Rossell, Jr. Ecology of a southern Appalachian wetland. Invited presentation. Asheville Men's Garden Club. April 1996.

Rossell, I.M., and C.R. Rossell, Jr. A holistic approach for monitoring restoration of a proposed wetland mitigation bank in western North Carolina. Connections: Transportation, Wetlands, and the Natural Environment Conference. Tacoma, WA. September 1996.

Rossell, C.R., Jr., and I.M. Rossell. Using the structure and composition of vegetation to guide restoration of wildlife habitat in forested wetlands. Connections: Transportation, Wetlands, and the Natural Environment Conference. Tacoma, WA. September 1996

Rossell, C.R., Jr. Habitat selection by small mammals in a southern Appalachian forest-gap bog. Natural Science Seminar. Warren Wilson College. September 1996.

Moorhead, K.K. Soil characteristics of three southern Appalachian bogs in western North Carolina. Annual meeting of the American Society of Agronomy. Indianapolis, IN. November 1996.

Rossell, C.R., Jr., and I.M. Rossell. Microhabitat selection by small mammals in a southern Appalachian forest-gap bog. Seventh Colloquium on the Conservation of Mammals in the South and Central United States. Black Mountain, NC. February 1997.

Wilds, S.P., C.R. Rossell, Jr., and I.M. Rossell. Avian species composition, landscape diversity, and vegetative structure in a partially disturbed southern Appalachian forest-gap bog complex. Association of Southern Biologists annual meeting. Greenville, SC. April 1997.

Moorhead, K. K. Tulula Bog/wetland restoration. National Consortium of Specialized Secondary Schools of Science, Mathematics, and Technology. Science field trip. June 1997.

Moorhead, K. K. Mountain bog restoration. TRB Mid-Year Workshop. Asheville, NC. August 1997.

Petranka, J.W. Direct and indirect effects of predators in structuring amphibian communities in an Appalachian wetlands complex. Invited seminar speaker. Department of Biology, East Tennessee State University. September, 1997.

Rossell, C. R. Jr., I.M. Rossell, K.K. Moorhead, and J.W. Petranka. Monitoring restoration of mountain wetlands using an ecosystem approach. Eighth Annual Southern Appalachian Man and the Biosphere Conference. Gatlinburg, TN. November 1997.

Wells, C.L. and I.M. Rossell. A comparison of the seed banks in a southern Appalachian fen and an adjacent disturbed floodplain. Eighth Annual Southern Appalachian Man and the Biosphere Conference. Gatlinburg, TN. November 1997.

Moorhead, K. K. Tulula wetlands restoration project. Invited speaker. Annual meeting of the Water Resources Research Institute. Raleigh, NC. April 1998

Colburn, K. C., and I. M. Rossell. The use of a bottomland ecosystem by the eastern box turtle, *Terrapene carolina carolina*. National Conference for Undergraduate Research. Salisbury, MD. April 1998.

Vitale, A. C., K. K. Moorhead, and G. Kormanik. A model of contiguity of disturbed and natural habitats of Tulula Bog, NC. National Conference for Undergraduate Research. Salisbury, MD. April 1998.

Hayes, L. J., and J. W. Petranka. Chemically mediated avoidance of a predatory odonate (*Anax junius*) by

American toad (*Bufo americanus*) and wood frog (*Rana sylvatica*) tadpoles. National Conference for Undergraduate Research. Salisbury, MD. April 1998.

Moorhead, K. K. Soil characteristics of southern Appalachian fens. Annual meeting of the Society of Wetland Scientists. Anchorage, Alaska. June 1998.

Moorhead, K. K., I. M. Rossell, C. R. Rossell Jr., and J. W. Petranka. Ecological restoration at a wetlands mitigation bank in western North Carolina. Connections 98: Transportation, Wetlands, and the Natural Environment. New Bern, NC. September 1998.

McCann, M., C. R. Rossell Jr., and I. M. Rossell. Assessing restoration of a floodplain forest on a population of eastern box turtle (*Terrapene carolina*). Poster presentation. Connections 98: Transportation, Wetlands, and the Natural Environment. New Bern, NC. September 1998.

Rossell, C. R. Jr. Song perch characteristics of golden-winged warblers in a disturbed floodplain in western North Carolina. Southeast Migratory Bird Workshop and Conference. Biloxi, MI. January 1999.

Moorhead, K. K., I. M. Rossell, J.W. Petranka, and C. R. Rossell. Tulula Wetlands Mitigation Bank, North Carolina. Abstracts, p.A-93. Annual meeting of the Society of Wetland Scientists. Norfolk, VA. June 1999.

Rossell, I. M. Mountain wetland ecology. North Carolina Statewide Wetland and Stream Management Committee Meeting. NC Arboretum, Asheville, NC. 1999.

Petranka, J. W. Direct and indirect effects of predators in structuring amphibian communities in a southern Appalachian wetlands complex. Invited Seminar. Appalachian State University. 2000.

Moorhead, K. K. Effects of drought on the water table of a mountain floodplain/fen complex. Abstracts, p.47. Annual meeting of the Society of Wetland Scientists. Chicago, IL. June 2001

Moorhead, K. K. A comparison of water-table depth using electronic and manual wells. Abstracts, p. 131. Annual meeting of the Society of Wetland Scientists. Lake Placid, NY. June 2002

Rossell, C. R. Jr. Effects of wetland restoration on breeding bird populations. Invited presentation. Elisha Mitchell Audubon Society. October 2003

Isbanioly, H. and Reynolds, B.C. The study of microarthropod communities in Tulula Bog. 5th Annual Southern Appalachian Conference on Arthropod biology. Appalachian State University. September 2003

Harp, E. and J. W. Petranka. Transmission of ranaviral infections in amphibian communities. National Conference of Undergraduate Research. Indianapolis, IN. April 2004

Holbrook, C. T. and J. W. Petranka. Importance of intraguild predation in structuring amphibian communities. National Conference of Undergraduate Research. Indianapolis, IN. April 2004

Moorhead, K. K. Geomorphology and stability of a restored southern Appalachian stream. Abstracts, p. 104. Annual meeting of the Society of Wetland Scientists. Seattle, WA. July 2004

Moorhead, K. K. and I. M. Rossell. Changes in plant community composition in wet and dry areas of a restored mountain floodplain. Abstracts, p. 98. Annual meeting of the Society of Wetland Scientists.

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Bell, D. W. and K. K. Moorhead. Influence of stream restoration on the hydrology of a mountain floodplain/fen complex. Abstracts, p. 55. Annual meeting of the Society of Wetland Scientists. Charleston, SC. June, 2005

Reynolds, B. C., J. Isbanioly, J. Hamel, and K. K. Moorhead. Differences in litter decomposition and microarthropod abundance among plant communities in a mountain floodplain/fen complex. Poster. Abstracts, p. 152. Annual meeting of the Society of Wetland Scientists. Charleston, SC. June, 2005.

Hamel, J.A. and B. C. Reynolds. Differences in soil microarthropod abundance from a mountain floodplain/fen complex. Poster. Abstracts, p. 140. Annual meeting of the Society of Wetland Scientists. Charleston, SC. June, 2005.

Reynolds, Barbara C. Jennifer Hamel, Jason Isbanioly, Leo Klausman, and Kevin K. Moorhead. From Forest to Fen: Microarthropod Abundance and Litter Decomposition in a Southern Appalachian Floodplain/Fen Complex (USA). Symposium on Soil Ecology. University of Georgia, Athens, GA. October 2005.

Harp, E. M. and J. W. Petranka. Ranavirus in wood frogs (*Rana sylvatica*): Potential sources of transmission within and between ponds. National meetings of Ecological Society of America, Memphis, TN. August 2006.

Undergraduate Research Publications

Wells, C. L., I. M. Rossell, and J. Perry. 1995. A comparison of the seed banks of adjacent disturbed and undisturbed North Carolina wetlands. Proceedings of the National Conference on Undergraduate Research IX:872-876.

Riddle, W. K. and I. M. Rossell. 1996. A microhabitat analysis of *Sarracenia purpurea* in western North Carolina bogs. Proceedings of the National Conference on Undergraduate Research X:1731-1735.

Cacka, J. E. and J. W. Petranka. 1997. Effects of wood frog (*Rana sylvatica*) predation on spotted salamaner (*Ambystoma maculatum*): Oviposition site selection. Proceedings of the National Conference on Undergraduate Research XI:1392-1396.

Rushlow, A. and J. W. Pretranka. 1997. Consequences of opportunistic predation by a primary consumer (*Rana*) on a predator (*Ambystoma*). Proceedings of the National Conference on Undergraduate Research XI:1397-1401.

Rash, W. J., D. I. Cahan, K. K. Moorhead, and K. E. Krumpe. 1997. The effect of carbon content on the redox potential and fermentation products of wetland soils. Proceedings of the National Conference of Undergraduate Research XI:1835-1839.

Vitale, A., K. K. Moorhead, and G. A. Kormanik. 1998. A model of contiguity of disturbed and natural habitats at Tulula Bog, NC. Proceedings of the National Conference of Undergraduate Research XII:1316-1320.

Colburn, K., and I. M. Rossell. 1998. The use of a bottomland riparian ecosystem by *Terrapene carolina carolina*. Proceedings of the National Conference of Undergraduate Research XII:1795-1799.

Brooks, G., and I. M. Rossell. 1999. Proximity to and use of water bodies by the eastern box turtle. Proceedings of the National Conference of Undergraduate Research XIII.

Alvarado, H. and I. M. Rossell. 2002. Effects of saturation on the revegetation of a recently disturbed wetland in Western North Carolina. UNCA Journal of Undergraduate Research.

Thorn, R. N. and K. K. Moorhead. 2004. Channel characteristics of the restored Tulula Creek after one year of flow. UNCA Journal of Undergraduate Research

Harp, E. and I. M. Rossell. 2004. Allozyme analysis of the ten-angled pipewort (*Eriocaulon decangulare*) in western North Carolina. Proceedings of the National Conference of Undergraduate Research XVIII.

Bell, D. and K. K. Moorhead. 2005. Stream Channel Stability of the Restored Tulula Creek after Three Years of Water Flow. Proceedings of the National Conference of Undergraduate Research XIX.

Schultz, M.N., I.M. Rossell, and J. Horton. 2005. Effects of water table level on annual growth and nitrogen content of tag alder (*Alnus serrulata*) in Tulula Wetlands Mitigation Bank. Proceedings of the National Conference of Undergraduate Research XIX.

Bell, D. W. and K. K. Moorhead. Influence of Stream Restoration on the Hydrology of a Mountain Floodplain/Fen Complex. Proceedings of the National Conference of Undergraduate Research XIX.

Reardon, D.E. and I.M. Rossell. 2006. How water table affects the feeding preferences of the woolly alder aphid. Proceedings of the National Conference of Undergraduate Research XX.

Sampson, S.D. and I.M. Rossell. 2006. A study of fish and habitat restoration in Tulula Creek. Proceedings of the National Conference of Undergraduate Research XX.

Klausman, L. and B. C. Reynolds. 2006. Decomposition and Microarthropod Abundance in Litter and Soil in a Southern Appalachian Wetlands Complex. Proceedings of the National Conference on Undergraduate Research. XX.

Grant proposals funded

W. Kris Riddle. The introduction of carnivorous plants to Tulula Bog. $2000 UNCA Undergraduate Research Program Summer Grant. 1995.

E. Marie McCann. Eastern box turtles at Tulula Bog: a seasonal study of microhabitat. $1000 UNCA Undergraduate Research Program Summer Grant. 1998.

Laura Dlugolecki. Heavy minerals of sediment samples from the Tulula and Nantahala Creek floodplains. $3,000 North Carolina Beautiful Fellowship. 2002-2003.

Rachel Thorn. Channel geomorphology and stability of a restored mountain stream. $3,000 North Carolina Beautiful Fellowship. 2003-2004.

Elizabeth Harp. Allozyme analysis of the ten-angled pipewort (*Eriocaulon decangulare*) in western North Carolina. $3,000 North Carolina Beautiful Fellowship and $2,000 UNCA Biotechnology Grant. 2003-2004.

David W. Bell. Influence of Stream Restoration on the Hydrology of a Mountain Floodplain/Fen Complex. $3,000 North Carolina Beautiful Research Fellowship, 2004-2005.

Mary Schultz. The effects of hydrology on the growth and stem nitrogen in *Alnus serrulata*. $4,000 North Carolina Beautiful Scholarship and $250 UNCA Undergraduate Research Program Fall Grant. 2004-2005.

Dawn Reardon. How water table affects the feeding preferences of the woolly alder aphid. $3,000 North Carolina Beautiful Research Fellowship and $350 UNCA Undergraduate Research Program Fall Grant. 2005-2006.

Salena Sampson. A study of fish and habitat restoration in Tulula Creek. $350 UNCA Undergraduate Research program Fall Grant. 2005-2006.

Undergraduate senior research projects

Hoyle, D.L. A study of seed germination in the rare red Canada lily. (UNCA Biology Department, 1994-1995).

Wells, C.L. A comparison of the seed banks of adjacent disturbed and undisturbed North Carolina wetlands. (UNCA Biology Department, 1994-1995).

Roberts, K. Ecological interactions between wood frogs and spotted salamanders in a western North Carolina bog complex. (UNCA Biology Department, 1995)

Riddle, W.K. Carnivorous plants at Tulula Bog. (UNCA Environmental Studies Program, 1995-1996).

Humphries, W. An insect survey of Tulula Bog. (UNCA Environmental Studies Program, 1996).

Kilpatrick, A. Natural regeneration of red maple (*Acer rubrum*) in a disturbed forest-gap bog complex. (UNCA Environmental Studies Program, 1996-1997).

Rash, W. The effects of soil organic matter content and redox potential on fermentation products from flooded hydric soils. (UNCA Environmental Studies Program, 1996-1997).

Colburn, K. The use of a bottomland ecosystem by the eastern box turtle, Terrapene carolina carolina. (UNCA Environmental Studies Program, 1997-1998).

Hayes, L. A study of chemically mediated avoidance of odonates by American toad and wood frog tadpoles. (UNCA Biology Department, 1997-1998).

Koenings, C. Ecological implications of predation of green frog tadpoles on wood frog eggs. (UNCA Biology Department, 1997-1998).

Vitale, A. A model of contiguity of disturbed and natural habitats of Tulula Bog. (UNCA Biology Department, 1998).

Brooks, G. Microhabitat preferences of the eastern box turtle: proximity to and use of water bodies. (UNCA Environmental Studies Program, 1998).

McCann, E.M. Eastern box turtles at Tulula Bog: a seasonal study of microhabitat. (UNCA Environmental Studies Program, 1998-1999).

deBettencourt, D. Species diversity of soil dwelling insects in Tulula Fen. (Departments of Biology and Environmental Studies, 1999)

Smith. M. Habitat use by golden-winged warblers in a disturbed western North Carolina floodplain. (UNCA Environmental Studies Department, 1999-2000).

Montgomery, T. A home range analysis of the eastern box turtle. (UNCA Environmental Studies Department, 1999-2000).

Guerry, C. and L. Lawson. Prevalence and distribution of *Aeromonas* and other gram-negative bacteria at the Tulula Wetlands. (UNCA Biology Department, 2000).

Anderson, A. Effects of predator chemicals on hatching time and morphology of amphibian larvae. (UNCA Biology Department, 2000).

Kesgen, J. Habitat partitioning by red and black chokeberry in a mountain fen. (UNCA Environmental Studies Department, 2000)

Shriver, T. Relationships between hydrology and soil properties of restored wetlands. (UNCA Environmental Studies Department, 2001)

Alvarado, H. Effects of saturation on the revegetation of a recently disturbed wetland in Western North Carolina. (UNCA Environmental Studies Department, 2002)

Losure., D. The habitat and plant associates of *Eriocaulon decangulare* in three southern Appalachian wetlands. (UNCA Environmental Studies Department, 2002)

Thorn, R. Channel characteristics of the restored Tulula Creek after one year of flow. (UNCA Environmental Studies Department, 2003)

Dlugolecki, L. Heavy minerals of sediment samples from the Tulula and Nantahala Creek floodplains. (UNCA Environmental Studies Department, 2003)

Isbanioly, J. Leaf litter decomposition within a mountain wetland mitigation bank. (UNCA Department of Environmental Studies, 2003-2004)

Harp, E. Transmission of ranaviral infections in amphibian communities. (UNCA Department of Biology, 2004)

Holbrook, T. Importance of intraguild predation in structuring amphibian communities. (UNCA Department of Biology, 2004).

Moyer, A. and L. Burley. Mechanisms of competitive interactions between *Rana sylvatica* and *Ambystoma maculatum*. (UNCA Department of Biology, 2004).

Harp, E. Allozyme analysis of the ten-angled pipewort (*Eriocaulon decangulare*) in western North Carolina. (UNCA Environmental Studies Department, 2004)

Stanton, R. and K. Zeman. Environmental modeling of the Tulula wetland hydrology. (UNCA Environmental Studies Department, 2004)

Bell, M. Detection and quantification procedures for fermentation products from flooded soils. (UNCA Chemistry Department, 2004)

Bell, D. Channel geomorphology and changes in hydrology from a restored mountain stream. (UNCA Environmental Studies Department, 2004-2006)

Schultz, M. The effects of hydrology on annual growth and stem nitrogen in *Alnus serrulata*. (UNCA Environmental Studies Department, 2005)

Reardon, D. How water table affects the feeding preferences of the woolly alder aphid. (UNCA Environmental Studies Department, 2006)

Sampson, S. A study of fish and habitat restoration in Tulula Creek. (UNCA Environmental Studies Department, 2006)

Klausman, L. Decomposition and Microarthropod Abundance in Litter and Soil in a Southern Appalachian Wetlands Complex. (UNCA Environmental Studies Program, 2005-2006).

Hamel, J.A. Differences in soil microarthropod abundance from a mountain floodplain/fen complex. (UNCA Environmental Studies and Biology Department 2004-2005).

Graduate Student Research Projects

Quinn, D. Geomorphology and Stability of the Realigned Channel at Tulula Wetlands Mitigation Bank. M.S. degree. Department of Forestry. North Carolina State University

Warren, R. The Impact of Woody Canopy Disturbance on Vegetation Diversity in a Southern Appalachian Wetland. M.S. Thesis. Department of Biology. Western Carolina University.

Agraz, V. The effect of hydrology on the annual net above-ground primary production (biomass) of *Juncus effusus* L. (soft rush) in a southern Appalachian mountain wetland. M.S. Thesis. Department of Biology. Western Carolina University.

Undergraduate students who have participated in research at Tulula.

Joe-Ann Lawrence	William Kris Riddle
Carolyn Wells	Paul Myers
Diane Ducharme	Mark Hopey
Rachel Reese	Rachel Moynihan
Christy Roberts	Kevin Caldwell
Jay Ham	Kevin Hining
Ford Mauney	Wesley Humphries

Andy Kilpatrick
Daphne Thomas
Richard Burgner
Marie McCann
Amy Burnett
Caroline Koenings
Abigail Vitale
Susan Starnes
Josiah Sheehan
Huma Alvarado
Todd Montgomery
Rayson Smith
Shane Hill
Susan Murray
Athena Anderson
Elizabeth Harp
Jenna Kesgen
Troy Shriver
Jason Isbanioly
Rachael Thorn
Laura Dlugolecki
Anna Moyer
Katherine Zeman
David Bell
Ted Williams
Julia Loyd-Cowder
Mary Schultz
John Ashley
Salena Sampson

Katie Underwood
Andrea Rushlow
Suzanne Konopka
Gretchen Brooks
Kevin Colburn
Laura Hayes
Kelly Booth
Cindy Byron
Mamie Smith
Robert Warren
Daniel deBettencourt
Andrea Oswald
Scot Waring
Katie Harmuth
David Losure
Kat Duhnam
Stacey Hatcher
James Martin
T.R. Russ
Ashley Aspinwell
Tate Holbrook
Rita Stanton
James Wood
Michael Bell
Louise Burley
Jennifer Hamel
Andrew Slack
Dawn Reardon
Leonardo Klausman

Appendix G. Previous Studies at Tulula Not Covered in This Report (See Moorhead et al. 2001a, Moorhead et al. 2002, and Moorhead et al. 2004 for details).

1. Delineation of hydric soils
2. Vertical hydraulic gradient in fen/floodplain areas
3. Soil characteristics of fen/floodplain areas
4. Plant surveys
5. Vegetation inventory of fen/floodplain areas
6. Seed bank study
7. Red maple surveys
8. Amphibian/reptile surveys
9. Ecology of the Eastern box turtle
10. Relationships between birds and their habitats
11. Golden-winged warbler song perches
12. Mammal surveys
13. Vegetation plantings and survival
14. Vegetation response to spoil removal
15. GIS – plant communities
16. Natural regeneration of woody plants
17. Vegetation dynamics of fen/floodplain areas
18. Vegetation dynamics of recently restored areas
19. Ecology of *Juncus effusus*