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FLOODPLAIN HYDROLOGY AFTER RESTORATION OF A SOUTHERN APPALACHIAN MOUNTAIN STREAM

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Abstract: Determining the success of restored wetland hydrology is often accomplished by documenting changes in wetland hydroperiod before and after restoration. Ideally, post-restoration hydropatterns would approach those that existed before site degradation. We evaluated the average monthly water-table levels of a mountain floodplain and fen wetland complex before and after restoration with manual wells that included seven or eight years of pre-restoration data and with electronic wells that included one or two years of pre-restoration data. Site restoration included reconstruction of a meandering 1.9 km stream channel to replace a previously straightened channel. A higher water table was noted within 50 m of the restored channel regardless of the length of pre-restoration assessment. Many of the manual wells further from the stream had insignificant changes in average monthly water levels, whereas higher water levels were common for the electronic wells regardless of proximity to the restored channel. The longer pre-restoration assessment period for the manual wells captured the climatic averages of rainfall and provided a more accurate description of pre-restoration conditions. The electronic wells provided the appropriate data to determine if a given area met the compliance aspects of wetland restoration, but a thorough assessment of hydrologic changes could not be accomplished with the electronic well data because of the lower annual rainfall during the shorter pre-restoration assessment. We recommend that pre- and post-restoration assessment periods account for rainfall variability when documenting changes in hydrology associated with wetland restoration in fluvial systems. If no control wetland or water-table data are available, periods of nearly-average rainfall are helpful for evaluating wetland hydroperiod before and after restoration.

Key Words: assessment periods, fen, hydroperiod, water table, wetland restoration

INTRODUCTION

Changes in wetland hydrology are common in fluvial systems when a stream channel has been modified. Channels have been straightened, dredged, dammed, diverted, and filled, any of which may alter the timing, amplitude, frequency, and duration of high water in adjacent floodplain wetlands. For example, Schilling et al. (2004) determined that channel incision lowered the water table of the adjacent floodplain from the stream edge to a distance of approximately 30 m. The success of restoring the hydrology of fluvial systems may often depend on the restoration of a stream channel. Wetland hydrology is influenced by a variety of factors, including the balance of water inflow and outflow, the surface contours of the landscape, and the sub-surface soil, geology, and ground-water conditions (Mitsch and Gosselink 2000).

The success of hydrologic restoration of a wetland is often based on the location of the water table measured in swallow wells (Myers et al. 1995). A temporal analysis of the high and low water table is defined as a wetland hydroperiod. A wetland hydroperiod affects both plant and animal communities, and restoring periods of high and low water must be mimicked to restore biodiversity and wetland functioning at the local scale (Zedler 2000). The wetland hydroperiod is a primary factor controlling fluctuations in the redox state (Comerford et al. 1996, Seybold et al. 2002), rates of decomposition (Day et al. 1989, Moore and Dalva 1997), primary productivity (Megonigal and Day 1992), plant distribution and growth (David 1996), and other ecosystem attributes. It is widely recognized that hydrology exerts a basic control over wetland structure and function (Mitsch and Gosselink 2000).

The hydroperiod also serves a useful purpose within the regulatory or compliance aspects of documenting restoration success. For compliance success, the high water table must be typically within 30 cm of the soil surface for a certain period of time

(12 to 21 consecutive days) during the growing season. Ecological success of wetland restoration is more difficult to determine and is complicated by the frequent need to place success within this regulatory framework (Kentula 2000).

Our ability to determine success of wetland restoration is often hampered by the insufficient time used to assess projects while they mature (Mitsch and Wilson 1996). Many projects are evaluated for short periods of time (three to five years) after restoration. Equally important for documenting success, however, is to have an appropriate period of time to evaluate a degraded site before restoration commences. Although undisturbed reference ecosystems play an important role in determining restoration success, we must evaluate actual site performance before and after restoration to determine the overall change in ecosystem structure and function. Unfortunately, it is common to find site restoration beginning after one or two years of data collection from a degraded site. This amount of data may be appropriate for certain features of ecosystems, such as existing plant community structure. Other features such as the hydroperiod that are dependent on climatic conditions, may require longer periods of time to document existing degraded site conditions. At issue is our ability to document the functional success of a wetland restoration project (Kentula 2000).

We evaluated the hydrology of a mountain floodplain and fen wetland complex for eight years prior to stream restoration and four years following restoration. The site was severely impacted in the mid-1980s during construction of a golf course. During construction, the bed of the stream 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 percent of the wetlands were disturbed by drainage and timber harvest during golf course construction. The North Carolina Department of Transportation purchased the site in 1994 to develop the first wetlands mitigation bank in western North Carolina. Restoration of the site included the re-meandering of a mountain stream. One of our objectives was to determine if stream restoration would raise the water table of the adjacent fluvial wetlands. A second objective was to determine if documented changes in water-table levels were influenced by length of time used for hydrology assessments.

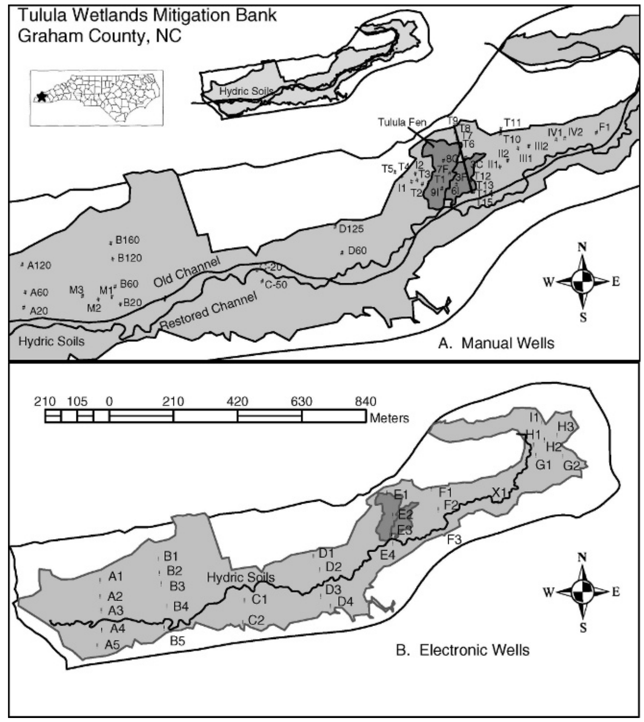

Figure 1. Maps showing location of manual wells (A) and electronic wells (B) used to assess site hydrology of the restored Tulula stream channel in Graham County, North Carolina. Manual wells A120, B160, and B120 were destroyed during site restoration and not replaced. Stream flow is from east to west. The light gray areas of the maps represent the extent of hydric soils on site. The solid black line in Map A near Tulula Fen represents a cross-section of wells illustrated in Figure 5.

SITE DESCRIPTION

Tulula Wetlands Mitigation Bank (35°17′N, 83°41′W) is a 98-ha area situated in the floodplain of the Tulula Creek in Graham County, North Carolina, USA (Figure 1). The mitigation bank was created to offset impacts of highway projects in western North Carolina, particularly in the Little Tennessee River basin (469,000 ha). The site was ideal for establishing a mitigation bank in the mountains of North Carolina because of its relatively large size and its need for large-scale restoration. Rainfall in this region is considered moderate, with precipitation in nearby Andrews, North Carolina averaging 161 cm annually (North Carolina Department of Transportation 1997). The topography of Tulula ranges from 785–800 m in elevation (Moorhead et al. 2001). The floodplain was mapped as a Nikwasi loam soil (Cumulic Humaquept) by the Natural Resources Conservation Service (unpublished data). The upland margins of the broad, level floodplain are bordered by forested areas and scattered seepage plant communities on adjoining slopes. Small ground-water-fed depressions, or fens, dispersed throughout the floodplain lead to Tulula being classified as a forest-bog complex, which is rare community type in this region of North Carolina (Weakley and Schafale 1994).

The original Tulula Creek was a low gradient, unconfined, alluvial pool-riffle channel (Montgomery and Buffington 1997) with a well-established floodplain. This channel was dredged to a highly entrenched, gully-type channel with a sinuosity $<$ 1.1 during a golf course development project. The dredged channel was 0.3 to 1.2 m below the historic streambed elevation. Over 1.9 km of the dredged channel was restored into a meandering pool-riffle channel. The restored channel sinuosity ranged from 1.2–1.4 and the average channel slope was 0.28%. The design of the new channel was based partially on the physical characteristics of a relict channel found primarily at the lower end of the site. The relict channel was used, when practical, as part of the new meandering channel. 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* Miller), 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 in the lower portion of the site was connected in two stages in May (Section V) and June (Section Va) 2002. The channel was built to produce bankfull discharge at a flood recurrence interval of every one to two years.

Concurrent with construction of the new channel, drainage ditches were blocked and filled and spoil was pushed back into the golf ponds. 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.

METHODS

Evaluation of site hydrology began in 1994 with a series of manual water-table wells installed across the site (Figure 1a). Many of the manual wells were located in a 4-ha floodplain/fen complex that served as a reference area for several research projects (see Tulula Fen in Figure 1a). The manual wells were constructed from 3.8-cm-diameter PVC pipe with horizontal slits spaced at 2 cm from the bottom up to 76 cm on the pipe. The wells were installed at a depth of 84 cm using a 7.6-cm-diameter dutch auger. The annular space between the pipe and augered hole was filled with river gravel, and the surface was sealed with subsurface soil having a clay content of 30%–40%. The soil was mounded at the surface of the installed pipe to enhance runoff away from the well. The manual wells were read two to four times per month with a metric tape rule marked with a water-soluble marker. 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, 2003). Rainfall was collected with a manual gauge in an open fairway near the fen at the same time that manual wells were measured.

Electronic water-table wells (RDS-40 wells, RDS Incorporated, Wilmington, NC, USA) were installed in July 2000 along transects that were perpendicular to the new channel (Figure 1b). The electronic wells were installed to a depth of 102 cm with an auger. The annular space between the pipe and augered hole was filled with fine sand, and the surface was sealed with a combination of bentonite and the subsurface soil. The electronic wells were programmed to record the water-table depth on a daily basis and downloaded every four to six weeks.

The data for both types of wells were converted to monthly averages to compare the pre- and post-restoration conditions. Monthly averages are commonly used to describe temporal variability in wetland hydroperiod. The monthly averages of daily and of less-frequent measurements of water table are remarkably similar (Shaffer et al. 2000). The monthly data were used to develop 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 the upper portion of the site (water was released early September 2001). The data for both manual and electronic wells were averaged by month and were statistically analyzed using a two-tailed Tukey's Test (TTest) to determine any significant differences in pre- and post-restoration water-table levels.

RESULTS

The success of hydrologic restoration at Tulula, like many wetland sites, was determined primarily by changes in water-table depth. The water-table data from the manual wells included seven to eight years of pre-restoration data and four years of post-restoration data. The pre-restoration data included three years of drought conditions (July 1998 through fall 2001) and several years of higher than average

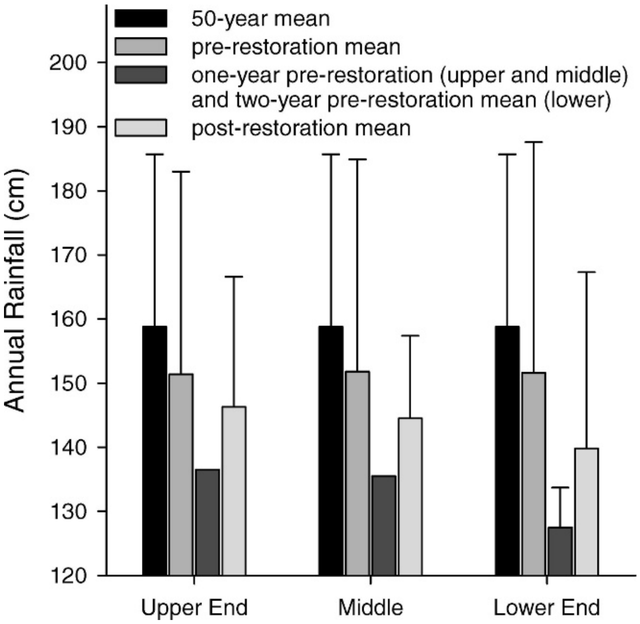

Figure 2. Mean annual rainfall (± SD) for the upper, middle, and lower portions of the site, based on the different dates of water release into the restored stream channel. Restoration and water release into the new channel began at the upper end and continued through the lower end.

annual rainfall, especially from 1994 through 1997. The mean annual rainfall for the seven years before water was released into the restored channel at the upper end of the site was 152 cm, compared to the 50-year mean of 159 cm (Figure 2).

The electronic wells were installed in 2000, resulting in a short pre-restoration hydrology assessment period of one to two years (depending on stream water release dates) compared with three to four years of post-restoration data. The annual rainfall before water release at the upper and middle portions of the site was about 136 cm, 23 cm less than the long-term mean (Figure 2). The electronic wells at the lower end of the site had two years of pre-restoration assessment, and the mean annual rainfall for those two years was 128 cm.

Using the data from both types of wells provided a better understanding of water-table dynamics and suggested a variety of trends for the site. Water-table elevations increased in some areas of the site, other areas had no appreciable change, and the water table dropped after site restoration in a few locations on the Tulula floodplain.

After restoration, the mean monthly water table rose in manual and electronic wells at the upper and middle portions of the site and close to the channel (Figure 3). These wells demonstrated a statistically significant increase ($p < 0.05$) from pre- to post-restoration water-table levels. The close proximity of these wells to the restored channel was likely the determining factor for higher water levels. In all, six manual wells (F1, T12, T13, T14, 6I, 9I) and six electronic wells (H1, G1, X1, E3, F2, D2) within 50 m of the restored channel demonstrated a statistically significant increase in water-table elevation. Manual wells 6I and 9I are located in Tulula Fen, and T12, T13, and T14 are part of a transitional area from floodplain to fen near the restored channel.

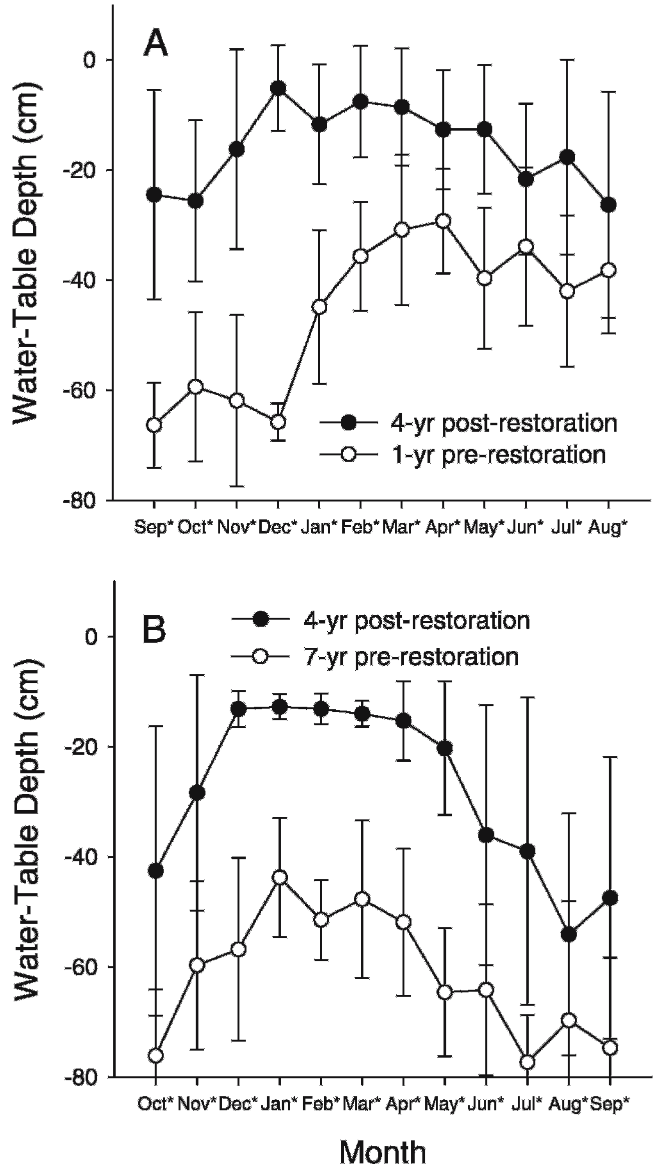

Figure 3. Hydrographs of mean monthly water-table data (± SD) from A) electronic well X1 and B) manual well T14 that showed a higher water table after stream channel restoration. Both wells are located at the upper end of the site within 30 m of the restored channel. Months with asterisks are significantly different ($p < 0.05$). Water depth of 0 is the soil surface.

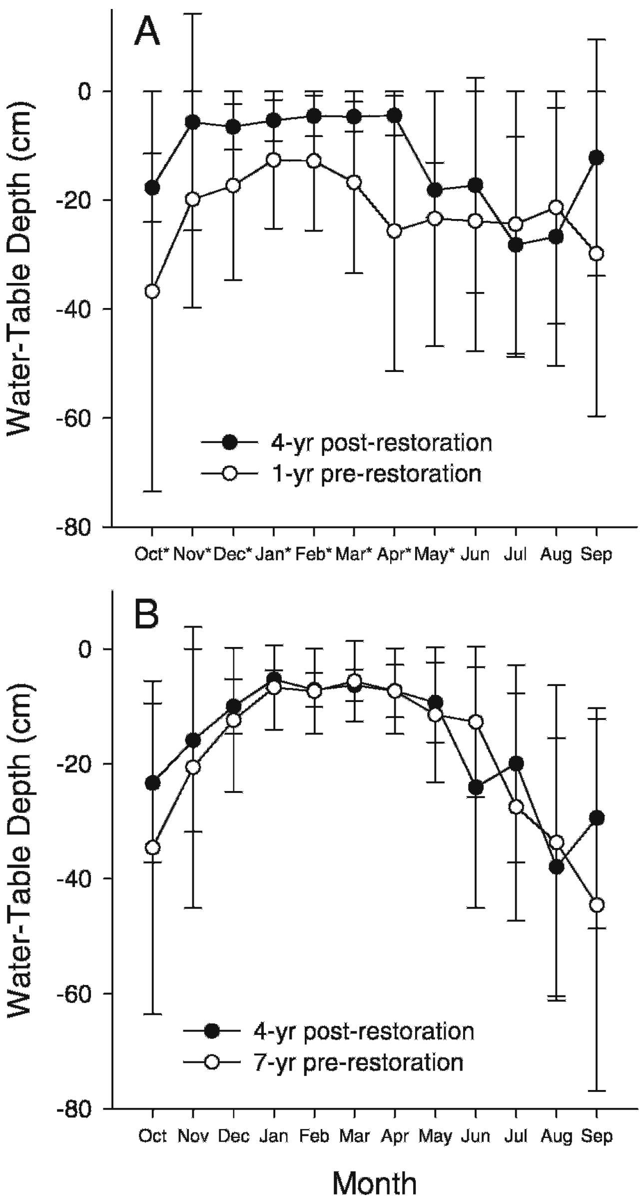

Figure 4. Hydrographs of mean monthly water-table data (± SD) from A) electronic well E2 showing some increases in water table after stream channel restoration and B) manual well 7f showing little change in water-table depth. The wells are located in Tulula Fen within 1 m of each other and about 45 m from the channel. Months with asterisks are significantly different ($p < 0.05$). Water depth of 0 is the soil surface.

The mean monthly water table did not change appreciably after restoration for manual wells located further from the restored channel at the upper end or middle of the site (Figure 4). However, the water tables of the electronic wells were higher after restoration. The increase in water-table levels based on data from electronic wells illustrated the difficulties of documenting restoration success with one or two years of pre-restoration hydrology data, particularly in conditions of below average rainfall. It also suggested that the longer term data from manual wells probably more accurately reflected the average range of site hydrologic conditions based on seven years of pre-restoration data.

A large cluster of manual wells near and in Tulula Fen (Figure 1A) provided a more detailed analysis of changes in site hydrology. The cluster included 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. As noted earlier, the water table rose in fen wells 9I and 6I. Both wells were closer to the restored channel relative to the four fen wells (8C, 3C, 3F, 7F) that showed no change in hydrology. The water table of wells on a transect (T1-T5) and floodplain (I1, I2) west of the fen dropped after site restoration. There was no logical explanation for the lower water table in this area of the Tulula floodplain after stream restoration. The water table noted in wells on two transects (T6-T9 and T10-T11) north of the fen showed no significant change in depth. The other transect runs between Tulula Fen and the restored channel (south of the fen); the wells on this transect (T12, T13, T14) had a greater water-table increase due to the proximity of the restored channel. The manual wells located on the Tulula floodplain east of the fen (II, III, IV wells) showed little difference in water-table depth after stream restoration. However, an isolated well located further east (F1) and closer to the restored channel had a significant increase in water-table elevation. Changes in the average monthly water-table depth for manual wells in April are shown as a cross-section of the Tulula floodplain in Figure 5.

Water-table levels of many electronic wells rose after site restoration, regardless of distance from the restored channel. Having one year of pre-restoration data for the electronic wells at the upper end and middle of the site limited our ability to demonstrate the impacts of restoration on water-table dynamics. Annual variations in rainfall also contributed to perceived improvements of hydrology after restoration. Determining the success of restoration based on hydrology was clearly compromised by the lack of long-term pre-restoration data for the electronic wells, coupled with the differences in rainfall before and after restoration.

At the lower end of the site, two years of pre-restoration data were available for the electronic wells. The water table rose in four electronic wells following restoration (A5, B1, B2, B3), while one showed no statistical difference. Two manual wells

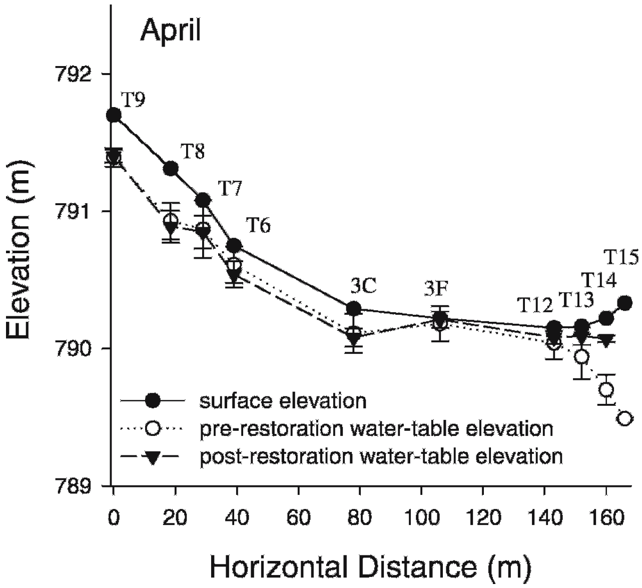

Figure 5. A cross-section of the Tulula floodplain (see Figure 1A for location) showing the mean monthly water-table depth (± SD) for the month of April in many manual wells before and after stream restoration. T12, T13, and T14 have a significantly higher water table after restoration. The restored Tulula stream channel is located about 30 m from T15.

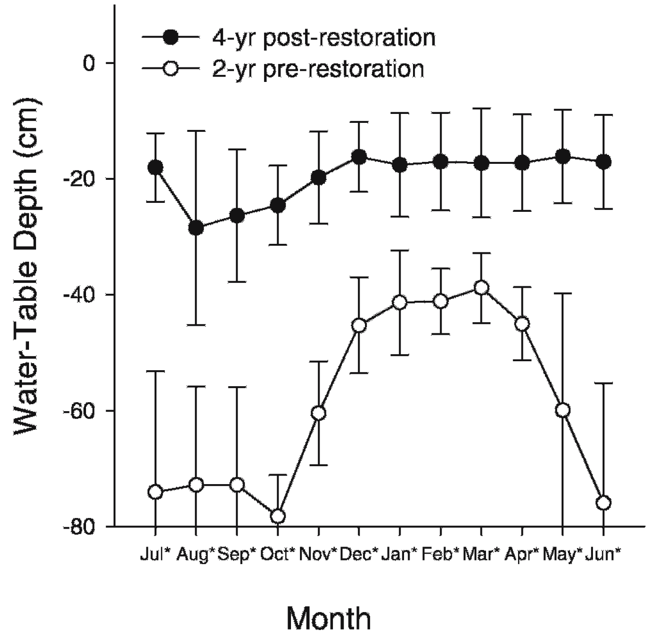

Figure 6. A hydrograph of the mean monthly water-table data (± SD) from electronic well B4 showing higher water levels due to beaver damming of the restored channel. Months with asterisks are significantly different ($p < 0.05$). Water depth of 0 is the soil surface.

(A60, M2), with eight years of pre-restoration data and four years of post-restoration data, showed no difference in water-table depth, while two other manual wells (B60, M3) had a lower average monthly water table after restoration.

The analysis of water-table data was more difficult near the channel at the lower end of the site because of the presence of beaver. Beaver initially built a dam at the lower end of the site in 1999. Some were trapped that year, but other beaver built more dams in 2000 and have remained ever since. Several of the manual (A20, B20, C20, C50, D20) and electronic wells (A3, A4, A5, B4, B5, C1, C2) were impacted by overbanking of water behind the beaver dams, with a typical hydrologic signature of a high water table throughout the year (Figure 6). The high water table attributed to beaver dams made it impossible to evaluate the effects of stream restoration on site hydrology at the lower end of the site. The overall area of influence of beaver dams and stream restoration on site hydrology is shown in Figure 7. A summary of changes in water-table depth across the site for individual wells is listed in Table 1.

DISCUSSION

A key to interpretation of changes in site hydrology of Tulula is the long-term pre-restoration dataset associated with the manual wells. The seven to eight years of data captured enough climatic variability to represent average hydrologic conditions of the site before restoration. The short-term pre-restoration data from the electronic wells did not capture the average rainfall for this particular project. The net result from using the electronic wells would be erroneous conclusions on hydrologic changes due to channel restoration. If rainfall is less than normal, or greater than normal, then water-table data are not easily interpreted (Vepraskas et al.

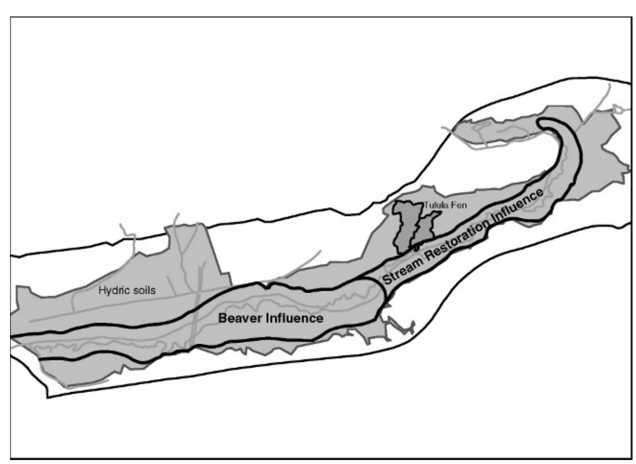

Figure 7. Composite map of Tulula restoration site showing areas of increased water table due to stream restoration or beaver activity.

Table 1. Summary of water-table changes at Tulula Wetlands Mitigation Bank.

Wells	Higher Water Table	No Change	Lower Water Table
Changes from Stream Restoration			
Manual			
Upper End	F1		
Middle	61, 91, T12, T13, T14	3C, 3F, 8C, 7F, II1, II2, III1, III2, IV1, IV2, T9, T8, T7, T6, T10	T1, T2, T3, T4, T5, T11, I1, I2, D125
Lower End		A60, M2	B60, M3
Electronic			
Upper End	I1, H1, H3, G1, G2, X1		
Middle	E1, E2, E3, F1, F2, D1, D2	D4	
Lower End	A5, B1, B2, B3		A1
Changes due to Beaver Activity			
Manual			
Lower End	A20, B20, C20, C50, D60		
Electronic			
Lower End	D3, C1, C2, A3, A4, B4, B5		
Unexplained Changes			
Electronic	A2, H2		

2006). However, measurements made during periods of normal rainfall may represent long-term averages (Sprecher and Warne 2000). Having average rainfall conditions for a site during typical short assessment periods is probably rare for many restoration projects.

Although the electronic wells provided the appropriate data to determine if a given area met the compliance aspects of a wetland restoration, an accurate assessment of hydrologic restoration associated with wetland restoration at Tulula could not be accomplished with the electronic wells. A further implication was our inability to prove conclusively that compliance wetland areas were the result of site restoration or simply a result from changes in rainfall before and after restoration. Finally, an inaccurate description of water-table dynamics associated with wetland restoration would limit our understanding of ecological changes that might occur at a restored site. For Tulula, the manual wells provided more information to address these issues because of the longer pre-restoration assessment of hydrologic conditions. We recommend that pre- and post-restoration assessment periods account for rainfall variability when documenting changes in hydrology associated with wetland restoration in fluvial systems. Periods of average rainfall (whether one or many years) are essential for determining changes in wetland hydroperiod before and after restoration.

The impacts of stream restoration on floodplain hydrology were restricted to a fairly narrow area surrounding the new channel (Figure 7), which is consistent with the results of Shilling et al. (2004). Overbanking has occurred once or twice at a few points along the restored channel, but flooding has been limited to areas within a few meters of the channel. Hence, the higher water levels measured in wells near the restored channel were a result of a higher water table in the floodplain. Earlier results suggested that the water table of the fen was influenced by ground-water inputs and rainfall but not hydrologically influenced by or influencing the straightened Tulula channel (Moorhead 2001). Since restoration, wells located in the fen and near the restored channel have a higher water table, suggesting that the elevated water table of the floodplain between the channel and the fen has created lateral ground-water flow into the topographically lower fen, or reduced dewatering of ground water being discharged into the fen. For comparison, Eli and Rauch (1982) concluded that fen areas of Cransville Swamp in West Virginia appear to contribute insignificantly to base streamflow.

Stream restoration has become a widespread practice in North America and Europe, with goals frequently focused on improving water quality, enhancing aquatic and riparian habitat, and stabilizing the physical features of a channel (Alexander and Allan 2006, Kondolf 2006). Rarely is stream restoration tied specifically to goals of improving site hydrology. The impacts of remeandering a stream on the water tables of adjacent floodplains appear to be fairly narrow in area, and other methods of improving site hydrology should be considered, especially in areas of broad floodplains. Our study also shows how important the climatic conditions of the pre- and post-restoration assessment period are for determining actual changes in hydrology that occur from site restoration. The changes in hydrology are fundamentally important to understanding an ecological response to site restoration.

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