River restoration strategies in channelized, low-gradient landscapes of West Tennessee, USA

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River restoration strategies in channelized, low-gradient landscapes of West Tennessee, USA

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ABSTRACT

West Tennessee has a complex history of watershed disturbance, including agricultural erosion, channelization, accelerated valley sedimentation, and the removal and reestablishment of beaver. Watershed management has evolved from floodplain drainage via pervasive channelization to include local drainage canal maintenance and local river restoration. Many unmaintained canals are undergoing excessive aggradation and complex channel evolution driven by upland erosion and low valley gradient.

The locus of aggradation in fully occluded canals (valley plugs) moves up-valley as sediment continues to accumulate in the backwater behind the plug. Valley plugs that cause canal avulsion can lead to redevelopment of meandering channels in less disturbed areas of the floodplain, in a process of passive self-restoration. Some valley plugs have brought restored floodplain function, reoccupation of extant historic river channels, and formation of a “sediment shadow” that protects downstream reaches from excess sedimentation. Despite the presence of numerous opportunities, there is presently no mechanism for including valley plugs in mitigation projects.

In 1997 a survey of 14 reference reach cross sections documented relations between drainage area and bankfull geometry of relatively unmodified streams in West Tennessee. Reassessment of seven of those sites in 2007 showed that one had
been dammed by beaver and that two sites could not be analyzed further because of significant vertical or lateral instability. In contrast to other regions of North America, the results suggest that stream channels in this region flood more frequently than once each year, and can remain out of banks for several weeks each year.

INTRODUCTION

West Tennessee, between the Tennessee River divide and the Mississippi River, provides a field laboratory for understanding the post-disturbance evolution of low-gradient drainage systems. Five major regional watersheds contribute flow to the Mississippi River: the Wolf, Hatchie, Loosahatchie, Forked Deer, and Obion Rivers (Fig. 1). Historical watershed disturbance in this region includes beaver removal, deforestation, pervasive channelization, levee construction, and wetland drainage (Wolfe, 1994; Diehl, 2000; Johnson, 2007). Within the context of steep, erodible sandy uplands, these activities have combined to generate gullies and sheetflow with attendant locally high sand loads and complex channel-valley responses, including the formation and growth of valley plugs (Happ et al., 1940; Diehl, 1994; Shields et al., 2000). This region is one of the most hydraulically altered landscapes in North America with hundreds of kilometers of drainage canals excavated in the last century to support agricultural and urban development of the low-gradient floodplains (e.g., Johnson, 2007). Channelization (sensu Brookes, 1988) in West Tennessee has not ended, but in the mid-1990s, watershed management goals became more complex with the addition of river and wetland restoration as competing elements of officially recognized management plans (e.g., GIWC, 1994; TN, 1994).

Human disturbance of this region, beginning with fur trapping in the late 1600s, set in motion what is essentially a long-term, large-scale experiment in fluvial landscape evolution. An understanding of the pre-EuroAmerican settlement conditions of West Tennessee is paramount for those involved in developing watershed policy here, and for those engaged in local or regional restoration projects. Just as important to future management is an understanding of the geometry and dynamics of extant relatively unmodified stream-floodplain systems in the region. The existing institutional paradigm of restoring only single-thread channels in this region may be flawed if “natural” (i.e., “presettlement”) conditions are the goal of restoration.

Geologic Setting

West Tennessee lies in the Coastal Plain geomorphic province of the Mississippi Embayment (Miller, 1974). The surface stratigraphy includes three main units (Fig. 1): (1) westward-dipping, poorly consolidated Upper Cretaceous and lower Tertiary sandy, pericoastal deposits exposed in the uplands; (2) Quaternary loess that forms thick deposits in the west and pinches out eastward; and (3) Quaternary alluvium in the valley bottoms (Miller et al., 1966; Miller, 1974). The regional physiography can be generalized as dissected rolling hills in the east that give way to low-gradient rivers in broad-floored valleys in the west. The westernmost edge of West Tennessee includes the floodplain and bounding bluffs of the Mississippi River. Digital elevation analysis shows that the landscape gradient rapidly decreases from 0.10 in the headwater streams to 0.0007 between the eastern uplands and the bounding bluffs of the Mississippi floodplain. Although West Tennessee lies in a mid-plate setting, neotectonic warping along the New Madrid Fault zone and Reelfoot Rift has produced pervasive basin asymmetry within the Mississippi Embayment (Cox et al., 2001; Garrote et al., 2006; Csontos et al., 2008) and...
may play a subtle role in reducing fluvial gradients in West Tennessee by eastward tilting of basement rocks.

**Historical Watershed Disturbance**

West Tennessee has a complex history of human disturbance. Lacking natural predators, beaver were no doubt ubiquitous in this region ca. 1700 (Nairne, 1988). West Tennessee valleys with drainage areas perhaps as large as 160 km² would have been pervasively dammed, ponded, and locally aggrading. Each dam would have inundated large areas of the valley floor, as they do in areas without beaver management today (Houston et al., 1995). Fur trapping after 1700 greatly reduced beaver abundance (Grabau, 2007, personal commun.). By the Chickasaw Cession of 1816, the streams may have still been adjusting to the loss of beaver. Without beaver dams to control grade, streams probably incised and developed knickpoints that cut headward, possibly extending drainage networks farther into erodible upland soils (Grabau, 2007). Crockett (1834) depicts the main branches of the Obion River as debris-choked and subject to prolonged valley-wide flooding, supporting the idea that accelerated upland erosion was active at that time.

Early economic development of West Tennessee included logging and agriculture on steep, sandy hillslopes. By the mid-1800s, upland erosion from agriculture was contributing to sediment deposition over formerly fertile bottomland (Hilgard, 1860). Widespread channelization in the 1900s was a response to the effects of this upland agricultural erosion (Ashley, 1910; Morgan and McCrory, 1910). Institutional efforts to drain the landscape and to relieve flooding through channelization and levees began in 1909 with the formation of “levee and drainage districts”:

… the County Court of any county in this State is hereby vested with the jurisdiction, power, and authority at any regular, special, or adjourned session to establish a drainage district or districts, and to locate and establish levees, and cause to be constructed, as hereinafter provided, any levee, ditch, drain, or watercourse, or to straighten, widen, deepen, or change any natural watercourse in such county, or provide for the same being done whenever the same will be of public utility or conducive to the public health or welfare and as hereby provided. (Private Acts, 2004, p. 24)

Most of the region was channelized by such districts, except for the largest rivers. Pervasive channelization of the drainage networks had the effect of increasing sediment yield to downstream reaches through post-channelization channel adjustment, as has happened more recently (e.g., Simon and Robbins, 1987; Simon, 1989a, 1989b, 1994). In response, the Federal Flood Control Act of 1948 was passed to improve flood control and drainage on 360 km of the West Tennessee tributaries to the Mississippi River (e.g., USCA, 2007) in an effort called the West Tennessee Tributaries Project (WTTP). Large-scale dredging peaked in Tennessee in the 1960s, when the U.S. Army Corps of Engineers (USACE) channelized the largest reaches of the Obion and Forked Deer Rivers. In 1959 the Obion–Forked Deer Basin Authority (OFDBA) was formed to maintain the flood capacity of the planned WTTP canals and all preexisting canals in the region (Private Acts, 2007).

In response to post-1970 federal environmental laws, the language of West Tennessee watershed management policy gradually shifted to include wetland restoration and preservation in addition to drainage. A federal court halted WTTP channelization because of an inadequate environmental impact report (TN, 1994; USACE, 1996; USCA, 2007), and the USACE agreed to purchase 12,950 ha of mitigation lands to compensate for the negative impacts of channelization (TN, 1994). Since that time, both permitted and nonpermitted dredging and lower-impact efforts (IAFWA, 1983) have been used to keep the canals functioning for flood control. By the 1990s, State environmental policy language clearly expressed the value of wetlands and acknowledged the ecological value of natural streams (GIWC, 1994). The mission of the OFDBA changed in 1996 from flood control through channelization to restoration of natural flood conveyance, and it was renamed the West Tennessee River Basin Authority (WTRBA) (USCA, 2007). The nascent WTRBA was empowered with the authority to “restore where practicable, in a self-sustaining manner, natural stream and floodplain dynamics and associated environmental and economic benefits” (USCA, 2007). The most recent watershed activities include a mixture of canal maintenance, canal decommissioning, and channel restoration. A range of river and wetland restoration designs, philosophies, and technologies are in use.

**Current Problems in Stream Restoration in West Tennessee**

A clear intent to improve environmental conditions and habitat in West Tennessee streams has been publicly documented (GIWC, 1994; TN, 1994; USCA, 2007; TSMP, 2007). Several key issues, however, constrain the potential for successful, long-term stream restoration. A realistic set of regional strategies, goals, and success criteria has not yet been agreed upon in the regulatory or resource-management communities (e.g., TDEC, 2004; Johnson, 2007; Paine, 2007). Reference reaches used to design or assess restoration projects are rare. Mitigation goals typically focus on reach-scale restoration (e.g., TSMP, 2007) rather than ecosystem-scale management or regional conservation. Excess sediment, large woody debris, and beaver activity continue to pose significant threats to restored stream reaches. The potential role of valley plugging and avulsion in restoration-conservation efforts has not been fully explored (Smith and Diehl, 2002).

In this paper we present a summary of bankfull geometry of relatively unmodified streams; give examples of restoration in West Tennessee, including unintentional large-scale self-restoration and intentional reach-scale restoration; and provide a discussion of research needs to improve restoration success and sustainability.
METHODS

The descriptions and conclusions presented in this paper are based on analysis of published and unpublished data. Data include U.S. Geological Survey (USGS) topographic maps, geologic maps, high-resolution aerial photography, digital elevation models, repeated cross-sectional surveys, and reconnaissance surveys by foot and small craft of disturbed, recovering, restored, and relatively unmodified fluvial systems in West Tennessee. The field and laboratory data, not all presented here, were collected in numerous visits to the region between 1996 and 2007. Partial data sets and results have been presented in various conference proceedings (e.g., Smith and Diehl, 2000, 2002), technical reports commissioned by the U.S. Environmental Protection Agency (e.g., Smith and Turrini-Smith, 1999a, 1999b), Tennessee Department of Environment (e.g., Smith and Rosgen, 1998; Smith, 1999) and nongovernmental organizations interested in natural resource protection (e.g., Smith, 2007).

Bankfull Geometry of Unmodified Channels

In 1997 we surveyed the bankfull geometry of 14 rivers in West Tennessee to evaluate and guide stream assessment and restoration efforts. Survey data are presented in Smith and Turrini-Smith (1999a, 1999b). An initial list of potential survey sites was generated from published ecoregion reference sites (e.g., Arnwine et al., 2000), map and aerial photographic analysis, and previous field experience. Sites were then eliminated if the watershed or local reach was significantly modified, as determined by site visit or map analysis. From the remaining sites, a single cross section was surveyed within a straight reach of channel, provided there were no obvious geomorphic signs of chronic bank erosion, aggradation, or degradation. Surveys were conducted where bankfull indicators were locally present, the channel geometry was not complicated by excess woody debris, and the morphology appeared typical of the reach. The cross-section surveys generally included 50–75 survey points tied to at least one, but usually two, benchmarks, except for Cypress Creek at Howell-Buntin Road, where no benchmarks were placed. The surveys typically include the bankfull channel, the natural levee system, and a significant width of floodplain on at least one side of the channel. The dominant particle size (e.g., silt-clay, sand, gravel) was recorded. A boat with an electronic or physical depth finder was used for surveying unwadable rivers.

Bankfull geometry was chosen to represent the stage at which the water would flow to the adjacent valley bottom, or, in the case of Harris Creek, the incipient floodplain. Bankfull elevation was selected either at the clear break in slope between channel and floodplain or at the elevation of the backswamp beyond natural levees. Seven of the surveyed sites were revisited and visually assessed in September 2007.

Our scope and methods biased us toward sites with single-thread channels within a few minutes’ walk or boat ride from access roads. In no case was bankfull geometry chosen from an existing analysis of flood-recurrence interval, eliminating one potential source of bias in geomorphic analysis. Except in the case of Harris Creek, which is an incised stream, the sites were typically in aggrading valley bottoms.

Valley Plug Evolution in Low-Gradient Valleys

Our description of valley plug evolution as one mode of canal failure, and the consequent processes of passive self-restoration, stem from several sources, including extant literature, aerial photography, USGS topographic maps (1:24,000 scale), and fieldwork. Happ et al. (1940) provided a detailed examination of the physical processes in low-gradient canals of the region. Our ideas on this topic evolved from numerous field trips to the region, including various combinations of surveys, small-craft traverses, foot traverses, and both fixed-wing and helicopter reconnaissance flights. Aerial photographs used to analyze valley plug evolution include Tennessee Department of Transportation (TDOT) black-and-white photographs from various years between 1979 and 2003, and at various scales ranging between 1:40,000 and 1:24,000, and digital imagery from TDOT at various resolutions. We also used digital black-and-white images of various scales downloaded from the USGS orthoquad series (USGS, 2008). The schematic maps of valley plugs presented in this paper were created by combining our field observations with feature tracings from recent digital black-and-white aerial photographs.

Review of Restoration Strategies

Descriptions of intentional restoration projects have been gathered through site visits, review of web-based literature (TSMP, 2007), and participation in design reviews (e.g., Smith and Rosgen, 1998) and project designs.

GEOMETRY OF RELATIVELY UNMODIFIED CHANNELS

Ideally, naturally formed alluvial streams that have fully adjusted their geometry to existing watershed conditions would be selected as reference reaches for research, assessment, and restoration design (Leopold and Maddock, 1953; Emmett, 1975; Dunne and Leopold, 1978; Hey, 2006; Rosgen, 2006). Unfortunately, pervasive watershed alteration and channelization have left no fully natural streams in West Tennessee. The Hatchie and Wolf Rivers have long unchannelized reaches, but both streams are affected by excess sediment from a great number of channelized tributaries (Diehl, 1994, 2000). The bankfull geometry of 14 relatively unmodified streams is provided in Tables 1 and 2. These sites include several unchannelized reaches and one river that has reestablished an unconfined, sinuous channel following canal avulsion. Each of the stream channels, except for Harris Creek, which is moderately entrenched, is situated within a broad, frequently flooded valley.
### TABLE 1. BANKFULL CROSS-SECTIONAL GEOMETRY FOR RELATIVELY UNMODIFIED STREAMS OF WEST TENNESSEE

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>DA (km²)*</th>
<th>Area (m²)</th>
<th>Width (m)</th>
<th>Depth (m)</th>
<th>Bed material</th>
<th>Channel type ³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Marshall Creek at Van Buren Rd.</td>
<td>15</td>
<td>2</td>
<td>5</td>
<td>0.4</td>
<td>Sand</td>
<td>E5/C5</td>
</tr>
<tr>
<td>2</td>
<td>West Fork Spring Creek at Van Buren Rd.</td>
<td>36</td>
<td>10</td>
<td>9</td>
<td>1.1</td>
<td>Sand</td>
<td>E5</td>
</tr>
<tr>
<td>3</td>
<td>Cypress Creek at Howell Buntin Rd.</td>
<td>43</td>
<td>7</td>
<td>6</td>
<td>1.2</td>
<td>Mud</td>
<td>E6</td>
</tr>
<tr>
<td>4</td>
<td>Spencer Creek at Hammlett Rd.</td>
<td>46</td>
<td>7</td>
<td>9</td>
<td>0.8</td>
<td>Mud</td>
<td>E6</td>
</tr>
<tr>
<td>5</td>
<td>Harris Creek above Potts Chapel Rd.</td>
<td>46</td>
<td>11</td>
<td>10</td>
<td>1.1</td>
<td>Sand</td>
<td>E5</td>
</tr>
<tr>
<td>6</td>
<td>Cypress Creek at Lower Brownsville Rd.</td>
<td>57</td>
<td>14</td>
<td>11</td>
<td>1.3</td>
<td>Sand-mud</td>
<td>E5/E6</td>
</tr>
<tr>
<td>7</td>
<td>Lagoon Creek near Estes Rd.</td>
<td>96</td>
<td>15</td>
<td>10</td>
<td>1.5</td>
<td>Mud</td>
<td>E6</td>
</tr>
<tr>
<td>8</td>
<td>Little Hatchie Creek above Powell Chapel Rd.</td>
<td>215</td>
<td>32</td>
<td>18</td>
<td>1.8</td>
<td>Sand</td>
<td>E5</td>
</tr>
<tr>
<td>9</td>
<td>Spring Creek at Sain Rd.</td>
<td>300</td>
<td>15</td>
<td>13</td>
<td>1.1</td>
<td>Sand</td>
<td>E5/C5</td>
</tr>
<tr>
<td>10</td>
<td>Wolf River at La Grange</td>
<td>510</td>
<td>25</td>
<td>14</td>
<td>1.8</td>
<td>Sand-mud</td>
<td>E5/E6</td>
</tr>
<tr>
<td>11</td>
<td>South Fork Obion River at Jarrell Bottoms</td>
<td>770</td>
<td>22</td>
<td>19</td>
<td>1.2</td>
<td>Mud?</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
<td>Hatchie River at Pocahontas</td>
<td>2150</td>
<td>96</td>
<td>32</td>
<td>3.0</td>
<td>Mud?</td>
<td>E6</td>
</tr>
<tr>
<td>13</td>
<td>Hatchie below Bolivar</td>
<td>3790</td>
<td>119</td>
<td>60</td>
<td>2.0</td>
<td>Sand</td>
<td>C5</td>
</tr>
<tr>
<td>14</td>
<td>Hatchie at Rialto</td>
<td>5910</td>
<td>132</td>
<td>40</td>
<td>3.3</td>
<td>Sand</td>
<td>C5</td>
</tr>
</tbody>
</table>

**Note:** Data from Turrini-Smith et al. (2000). See Figure 1 for general location.

*DA—drainage area for cross section.

Depth—area/width.

Level II stream classification from Rosgen (1994). Streams near the border of two types are given two classes.

### TABLE 2. DESCRIPTION OF SITES LISTED IN TABLE 1

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Re reconnaissance notes on or before Sept. 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Marshall Creek at Van Buren Rd.</td>
<td>Ponded by beaver dam before March 2007</td>
</tr>
<tr>
<td>2</td>
<td>West Fork Spring Creek at Van Buren Rd.</td>
<td>Not visited</td>
</tr>
<tr>
<td>3</td>
<td>Cypress Creek at Howell Buntin Rd.</td>
<td>Low bed load because site is located downstream from valley plug; site appeared stable</td>
</tr>
<tr>
<td>4</td>
<td>Spencer Creek at Hammlett Rd.</td>
<td>Not visited</td>
</tr>
<tr>
<td>5</td>
<td>Harris Creek above Potts Chapel Rd.</td>
<td>Rapid bank erosion left several centimeters of erosion pins exposed; 9 cm of deposition on benchmarks; bedrock influence</td>
</tr>
<tr>
<td>6</td>
<td>Cypress Creek at Lower Brownsville Rd.</td>
<td>5 cm of deposition on benchmarks; wood accumulation dam located upstream from site; located downstream from valley plug</td>
</tr>
<tr>
<td>7</td>
<td>Lagoon Creek near Estes Rd.</td>
<td>Not visited</td>
</tr>
<tr>
<td>8</td>
<td>Little Hatchie Creek above Powell Chapel Rd.</td>
<td>3 cm of deposition on benchmarks; site appears unchanged</td>
</tr>
<tr>
<td>9</td>
<td>Spring Creek at Sain Rd.</td>
<td>3 cm of deposition on benchmarks; cross-section site stable because of cypress knees; site no longer characteristic of reach, which has widened; several tributaries have valley plugs</td>
</tr>
<tr>
<td>10</td>
<td>Wolf River at La Grange</td>
<td>3 cm of deposition on benchmarks; site appeared stable; located downstream from valley plug</td>
</tr>
<tr>
<td>11</td>
<td>South Fork Obion River at Jarrell Bottoms</td>
<td>Not visited in 2007 (within valley plug system)</td>
</tr>
<tr>
<td>12</td>
<td>Hatchie River at Pocahontas</td>
<td>Not visited in 2007 (located below valley plugs)</td>
</tr>
<tr>
<td>13</td>
<td>Hatchie below Bolivar</td>
<td>Not visited</td>
</tr>
<tr>
<td>14</td>
<td>Hatchie at Rialto</td>
<td>Not visited</td>
</tr>
</tbody>
</table>
Determination of bankfull stage represented our best assessment of the point of incipient flooding of the adjacent broad valley floor or backswamp without prior knowledge of stage recurrence interval. Lowland streams in this region flood the valley floor more frequently than annually, and the larger channels are commonly out of banks for several weeks at a time, so there was little risk of misidentifying a terrace as bankfull elevation. For example, USGS hydrologic data and field surveys indicate that the Hatchie River at Rialto, Tennessee, has a bankfull discharge of ~150 m³/s (Fig. 2). Based upon the most recent 40 yr of record, 200 m³/s is exceeded ~14% of the days in the record, or 50 d/yr on average (Fig. 3). The Log-Pearson type III return period for bankfull discharge at this site is 1.02 yr, but the river floods more frequently than once each year, illustrating the limits of using Log-Pearson type III analysis of annual flood series data to assess return periods of frequent flows (e.g., Dunne and Leopold, 1978). This gauge is representative of other gauges in the region.

In September 2007, 10 yr after the original survey, we revisited 7 of the 14 surveyed sites (Table 2). All seven sites had clear indicators of floodplain inundation, and most had several centimeters of floodplain sediment covering benchmark caps. Of the seven revisited sites, one is now a beaver pond, one has excessive erosion and is bedrock influenced, one is stable only because of the strength of the knee of a local tupelo tree, and four appeared relatively unchanged on the basis of site photos and memory (Table 2). Figures 4 and 5 provide the bankfull geometric plots of the remaining 12 sites, with Harris Creek and Spring Creek removed. Elimination of these two creeks did not significantly change the equations relating drainage geometry to drainage area, and R² values slightly improved.

Hidinger and Morgan (1912) surveyed cross sections on the Hatchie River in comparable locations with this study (Figs. 4, 5). Although we cannot directly compare cross-section sites, we note that the river channel appears to have decreased in depth by a few meters and has lost cross-sectional area over the 85 yr since 1912 (Fig. 4). Widths have been steady over the same period (Fig. 5). Recent shoaling of the Hatchie River was quantified by Diehl (2000). Alternatively, the Hatchie River may have remained stable for 85 yr, given that the same data differences would have resulted if Hidinger and Morgan (1912) had used the natural levee tops as bankfull, rather than the local points of incipient flooding (sporadic swales eroded through natural levees), in their geometric calculations.

In contrast to unmodified streams, the channelized rivers (drainage canals) of West Tennessee are straight, earthen drainage canals with levees or spoil on one or both sides (Fig. 6). First- and second-order streams typically terminate upstream in the weak sandy bedrock underlying the eastern rolling hills. Gullying and headward extension of the first-order channels in response to channelization, cultivation, and deforestation increases the sand yield to the low gradient trunk streams (Happ et al., 1940; Simon, 1989a; Diehl, 1994). An example of a longitudinal profile of one headwater stream of the Obion River shows headwater gradients ranging from 0.06 to 0.12, but then abruptly flattening to a slope of ~0.0003 (Fig. 7). This break in slope, where sediment-laden headwater streams terminate on a flat floodplain, is a typical place for high sedimentation rates, trunk stream occlusion, and valley plug growth (Happ et al., 1940).

**CHANNEL EVOLUTION OF VALLEY PLUGS AND PASSIVE RESTORATION**

Happ et al. (1940) coined the term *valley plug* to describe the processes and deposits resulting from an occluded canal or stream channel. The term is widely applicable in West Tennessee, where high sediment and debris yield have led to canal blockages in numerous places in all the major river basins. Valley plugs commonly result from excess sand load where channel flow is impaired. The sand originates in eroded uplands and tributary fans. Flow impairment can be initiated by beavers, large wood accumulations, or poorly drained road and railway crossings. In

![Figure 3](specialpapers.gsapubs.org)  
**Figure 3.** Left scale is number of days of flow in 40 yr of daily average series data at Hatchie River at Rialto stream gauge. Right scale is percentage of non-exceedance cumulative frequency, showing that 150 m³/s is not exceeded on ~86% of the days of record (is exceeded on 14% of the days).
most cases, once the canal is plugged, the valley bottom becomes perennially ponded, killing the bottomland forest and leaving an open marsh environment. The upstream end of the plug can grow upstream through sediment deposition in ponded water. As aggradation continues, the valley bottom may become dry enough to support bottomland hardwood forests.

Many evolutionary pathways are possible in the valley bottom, once a valley plug forms (Happ et al., 1940; Smith and Diehl, 2002). Some of these pathways passively lead to a self-restored river-floodplain system that reoccupies the floodplain adjacent to an occluded canal. We describe two self-restored river reaches below. A theme in these two examples is that a valley plug can effectively decommission a canal and trap excess sediment. Trapping sediment has two effects—aggrading the valley bottom of swamped valleys to a point where hardwoods can exist, and providing a “sediment shadow” that reduces sand transport and deposition downstream from the plug. The time required for passive self-restoration to occur can vary from nearly instantaneous, where avulsed flow leads directly to an extant relict channel, to decades, where avulsed flow reoccupies a part of the floodplain where no relict pre-channelization channels exist.

Cypress Creek (McNairy County)

Recent aerial photography (TDOT, 1979–2004) showing relict channel features indicates that Cypress Creek (Fig. 8) was once a single-thread, low-gradient (0.0001), sinuous (k = 1.9) stream. The creek probably had a sand bed and a broad (2 km), forested
Beginning early in the twentieth century, channelization and straightening of Cypress Creek and many of its tributaries allowed agricultural and urban encroachment on the Cypress Creek floodplain. It is likely that accelerated upland erosion and incised tributaries delivered the voluminous sand load and large woody debris that have chronically impaired the Cypress Creek canal. Although the complete history of canal occlusion is not known, local blockages are visible in a 1979 aerial photograph. By 1999 the blockages had grown to form a 2.1-km-long debris jam (38,000 m$^3$) that forced most of the flow from the canal onto the right floodplain through a well-developed crevasse-splay system (Fig. 8). Boat and foot reconnaissance between 1999 and 2003 documented the flow paths shown in Figure 8. After leaving the canal, water flowed ~750 m laterally across the floodplain in numerous distributary channels toward the topographic low of the valley bottom and then turned to flow down the valley axis (Fig. 8). Flow alternately reoccupied reaches with anastamosing small channels and remnant channels of pre-channelized Cypress Creek. Between 1992 and 2003 (Fig. 8) the head of the canal blockage had episodically migrated up-valley at an average rate of 200 m/yr.

Although there has been no human effort to restore this disturbed valley bottom, a new riverine system has naturally evolved to have many of the characteristics of a “restored” river. A key component of the restoration is sediment management. The excess sand is trapped at the head of the system in the crevasse splay (Fig. 8), which provides a sediment shadow for the channel reaches downstream. Some of the fine sediment settles out in relative calm water that ponds as the water turns from lateral to axial flow at the toe of the crevasse splay. The water exiting the 5.6-km-long “self-restored” reach is free of sand and has improved clarity compared with the water entering the reach. The self-restored channel-floodplain system grew to at least 2.5 km in length before nonpermitted dredging cleared the canal and caused abandonment of the crevasse system in 2006.

**Jarrell Bottoms (South Fork Obion River)**

The South Fork Obion River at Jarrell Bottoms (Figs. 1, 9) historically flowed in a sinuous, single-thread river channel that
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Figure 8. Map of Cypress Creek (McNairy County) as it appeared in a 2003 aerial photograph. Some details derived from a 1983 7.5-min U.S. Geological Survey topographic map and from foot and canoe traverses. Arrows show main water-flow paths at baseflow conditions. See Figure 1 for location.

Figure 9. Map of Jarrell Bottoms valley plug system on South Fork Obion River. Details derived from aerial-photo and topographic-map interpretation and canoe traverses. Arrows show main water-flow paths at baseflow conditions. Three blockages on canal are named upper, middle, and lower, from right to left. See Figure 1 for location.
occupied a 1- to 2-km-wide forested floodplain. Channelization and levee construction isolated flow from the natural channel and floodplain. The South Fork Obion River canal is now occluded in three places at Jarrell Bottoms, and flow has been naturally restored to a long reach of pre-channelized river channel (Diehl, 1997; Fig. 9). A reach of that reoccupied channel was selected for a reference reach survey (site 11 of Table 1).

The South Fork Obion River canal was first blocked by excess sediment from Reedy Creek (Fig. 9). The canal avulsed upstream from that blockage, and the canal has remained blocked upstream from Reedy Creek (middle blockage of Fig. 9). A new bypass canal was excavated to reattach the mouth of Reedy Creek to the South Fork Obion River canal at a point farther west than the first (Fig. 9). The original Reedy Creek canal was then re-excavated after the bypass filled in with sediment (Fig. 9). Renewed sediment from Reedy Creek then occluded the South Fork Obion River canal downstream from the mouth of the bypass (lower blockage of Fig. 9). The third occlusion (upper blockage of Fig. 9) formed just downstream from the railroad bridge and adjacent U.S. Highway 79 bridge.

The valley plug system is now 5.8 km long, located between U.S. Highway 79 and Christmasville Road (Fig. 9). Excess sediment entering the system from the South Fork Obion River canal is trapped in a 200-m-long delta downstream from the Highway 79 bridge. Excess sediment from Reedy Creek is filling the South Fork Obion River canal at the head of the lower blockage (Figs. 9, 10) and is forming crevasse-splay deposits downstream from numerous avulsion channels (Figs. 9, 10). Downstream from these sediment shadows the South Fork Obion River occupies a network of anastomosing channels that gradually coalesce into a single-thread, meandering channel in the floodplain north of the mouth of Reedy Creek. The South Fork follows ~4 km of its natural channel from that point to Christmasville Road. Just downstream from Christmasville Road, most flow reenters the canal through a short cutoff that has formed since 1991. Road crossings strongly influence self-restored systems because they typically have only one or two major openings, sometimes directing restored channel flow back to a canal.

The depth of the reestablished main channel is adequate for small boats, even during summer low flow. Hunters and fishermen maintain a boat trail passable by canoes and johnboats through most of Jarrell Bottoms by cutting small gaps in drift that blocks the dominant channel. In multiple-channel reaches, these gaps concentrate flow in the deepest channel. Boat-trail maintenance is contributing to the reestablishment of a single main channel throughout Jarrell Bottoms.

**INTENTIONAL RESTORATION DESIGNS AND PROJECTS**

In the 1990s watershed-management policy shifted to include valuing wetland and floodplain restoration (Johnson, 2007). These efforts have included a range of ideas including a 24-km-long dual-channel system, natural channel design using rock and wood structures, and simple augmentation of self-restoration processes. We provide an example of each of these approaches.

**Dual-Channel Restoration for Low-Gradient Channels**

*(Middle Fork of Forked Deer River)*

The Middle Fork Forked Deer River (Fig. 1) prior to channelization had a sinuous course within a wide floodplain (Fig. 11). Drainage districts dug long, straight canals in the floodplain following the 1909 Drainage Act (Private Acts, 2004). The WTTP included plans for enlarging the Middle Fork Forked Deer canals, but the WTTP dredging was halted before that part of the work began. In 1992, Tennessee requested that the WTTP be reformulated to embody “environmentally sensitive” ways to “reduce flood damage, reduce erosion, restore floodplain integrity, and improve water quality” (TN, 1994). One of several locations where this new approach would be tried was the Middle Fork Forked Deer River canal (Fig. 11).

In response to the reformulated WTTP, the USACE produced a restoration design for 24 km of the Middle Fork Forked Deer River that included a two-part system. One part was a sinuous “bankfull” channel that would generally follow the extant remnant meanders and probable path of the historic river channel (Fig. 11; USACE, 1996; Doeing et al., 1996). This “bankfull” channel was to mimic the natural functions and benefits of the historic channel (USACE, 1996). The second part was an improved canal system in the place of the existing canal (Fig. 11). The two systems would intersect at six places, where 1.1-m-tall concrete weirs would deflect baseflow, up to 8.5 m$^3$/s, into the historic meanders. The canals were proposed to carry floodwater in excess of that diverted to the meandering channels.

Smith and Rosgen (1998) pointed out a number of flaws in the proposed plan. Design problems included an undersized and
disproportionate “bankfull channel” (Fig. 12), a large uncertainty about bed load and large woody debris accumulation where flow separation occurs at the 90° channel intersections, and a large, in-channel sediment basin that would require 10 clean-outs per year. Smith and Rosgen (1998) also pointed out that high-stage flow conveyance was impossible in a leveed canal that repeatedly intersects a smaller river that has low banks. The plan was not implemented.

**Incised Headwater Channel Restoration (North Fork Mud Creek)**

The Tennessee Stream Mitigation Program (TSMP, 2007) is a nonprofit organization created in 2002 to enhance or restore impaired streams. This program has completed several restoration projects in West Tennessee using principles of natural channel design (Rosgen, 2006). This program is the main mitigation program for the Tennessee Department of Transportation, so it will be the chief purveyor of restoration activities in Tennessee into the foreseeable future. We provide a description of North Fork Mud Creek (Fig. 1; Carroll County), as a sample of river restoration practices employing natural channel design with hard structures for incised headwater channels. Although the project lies a few kilometers east of the Tennessee River divide (Fig. 1), its physical setting and geologic context are identical to headwater streams west of the divide, where our studies have focused.

The North Fork Mud Creek project, completed in December 2006, includes 4.3 km of constructed channel along first- and second-order streams leading to Big Sandy Creek. The preexisting conditions included a deeply incised creek channel with tall, failing banks of weak sandstone (Fig. 13). Restoration techniques on most of the site employed “priority-two” restoration techniques of Rosgen (1997). The restored system is a sinuous, riffle-pool channel with a narrow floodplain bounded by tall terraces (Fig. 14). Rock and log structures are incorporated throughout the project for grade control, hydraulic roughness, and habitat diversity. For example, most straight reaches include cobble and pebble rock riffle constructed of angular limestone. While wood is a common component of local rivers, hard rock such as limestone is unknown in the region. Natural rock riffles are dynamic features constructed by the temporary residence of gravel that is gradually transported downstream and renewed from sources...
upstream. If the North Fork Mud Creek riffles are also dynamic features, they will eventually disappear through transport or burial by sand, which is the native bed load in the region.

Natural Channel Design for Low-Gradient Channels (Crooked Creek, Carroll County)

The Carroll County Watershed Authority was required to design and construct several kilometers of new sinuous stream channel as mitigation for a new 395 ha reservoir constructed for recreation and improved county tax basis (CCWA, 2000). The mitigation project will decommission several kilometers of functioning Crooked Creek drainage canal, and will redirect flow to a newly excavated sinuous channel within a broad floodplain historically used for corn and other agriculture. The design is complete, and construction will occur over 2 yr, starting in 2008. The new channel of Crooked Creek (Fig. 1) will drain a 72 km² watershed. The chief goal of the new channel is frequent flooding and draining of the broad floodplain in support of new wetlands and bottomland forest that will be cultivated there. In advance of channel design, a new USGS stage gauge was installed just upstream from the site, 12 shallow groundwater-monitoring wells were installed, and the site was surveyed in detail.

The channel size (Fig. 6) and planform were derived from a subset of the regional reference reaches (sites 1, 2, 6, and 8 of Table 1), local historic remnant channels, and one-dimensional hydraulic modeling. The reference sites were selected because they match the conditions of the Crooked Creek setting in several ways: They are sand-transporting streams not located in the sediment shadow of a valley plug; they have bed material of similar size; and they span the appropriate drainage area. Coincidentally, the design channel depth derived from the reference stream data is the deepest that can exist between the vertical constraints imposed by the existing floodplain (channel top) and the grade of the canal (channel bottom) to which the new channel must connect in two places. The only way to achieve a larger channel that maintains the width-to-depth ratio of reference streams would be to import an enormous volume of sediment to raise the floodplain or to construct continuous levees, which would counter the goal of floodplain function. The last 25% of new channel will be less deep than the rest because the landscape drops in elevation as compared with the canal where the new channel must connect. We anticipate floodplain aggradation along the entire site, especially in the last 25% of the project.

Reach-scale restoration efforts may be problematic if excess sand is entering the system from disturbed drainage basins. Although sediment transport was not directly measured in the canal upstream from the project area, helicopter, field, and canoe reconnaissance, and aerial photographic evidence, suggest that the Crooked Creek watershed is not a chronic source of excess sediment. Independent evidence for relatively low perennial sediment yield is that the drainage canal, which was constructed in 1915, has required no re-dredging (David Salyers, West Tennessee River Basin Authority, 2007, personal commun.). Thus, the canal is one geometric solution that is in steady-state equilibrium. The design channel has roughly the same geometry as the canal, if the canal levees were removed (Fig. 6). Bed-load transport modeling (Ackers and White, 1973) of well-sorted 0.29 mm sand confirms that the design channel capacity will be similar to the canal capacity in flows up to bankfull. Gauge analysis shows that bankfull conditions will be exceeded several times each year. Such conditions will lead to floodplain aggradation, which is beneficial, given the low relative elevation of the valley bottom. However, frequent sand deposition on the valley floor may pose a challenge to young trees planted during restoration. Monitoring will determine if valley-bottom aggradation should precede forest replanting.

It has been stated that hard structures are used in stream design to give riparian vegetation a chance to become established as the primary protection from bank erosion. A unique aspect of the Crooked Creek project is that flows will not be introduced to the channel for at least 1 yr after construction. Densely planted riparian woody species and grasses will have a year or more to mature into bank-stabilizing thickets before flow is fully avulsed from the canal. Large woody debris will be gradually recruited from upstream and stream-side sources.

Ditching and Levee Breaching for Low-Gradient Channels (Middle Fork of Forked Deer River at Law Road)

When drainage canals fill and fail to drain the land, farms get flooded, and landowners occasionally attempt to improve drainage. Anecdotal evidence, combined with reconnaissance fieldwork, can sometimes reveal the effects of these landowner projects. When the Middle Fork Forked Deer River drainage canal became occluded by sediment near Law Road, the landowner excavated a small ditch to redirect the flow from the canal to a nearby remnant meander of the historic river channel. This
pilot channel enlarged and became the primary base-flow channel. So, with little effort, this landowner inadvertently augmented self-restoration of this river system. The restored reach is >1 km long and is functioning at this writing.

**DISCUSSION**

West Tennessee has a long history of watershed disturbance, culminating in pervasive channelization commencing in 1909. In keeping with contradictions in wetland policy at the federal level (Votteler and Muir, 1996), the policy juxtaposition of canal maintenance and stream restoration in West Tennessee provides a complex setting for modern watershed managers.

The term restoration has many possible working definitions. One definition is the restoration of a site to a preconceived ideal of the fluvial landscape that would be present in the absence of human disturbance (e.g., Wohl and Merritts, 2007). In keeping with that philosophy, Tennessee stream mitigation guidelines require contractors to “return the channel to its most probable natural state, given the individual local constraints of the project location and watershed conditions” (TDEC, 2004). In pre-European West Tennessee, as now, the most probable natural state of much of the landscape is arguably a beaver pond. If restoration of “natural conditions” were the goal for West Tennessee streams, then the practice of beaver eradication would have to cease (e.g., Houston et al., 1995). After a few decades of this ecosystem-based management strategy, the valleys with drainage areas <~160 km² might resemble our view of the pre-European regional setting: forested, locally ponded, slowly aggrading valleys. The sediment shadow downstream from beaver populations would reduce sediment impacts on larger single-thread streams that are too big for beaver to dam. In current practice, however, beaver are considered pests and a threat to restoration projects; a beaver pond would be deemed a failed restoration project.

River restoration in West Tennessee ranges from unmanaged canal avulsion to precisely constructed pool-riffle reaches employing imported rock (e.g., North Fork Mud Creek). The immediate results of these activities include canal decommissioning, reestablishing floodplain function and bottomland forest, sediment control (valley plugs), habitat improvement, erosion control (e.g., North Fork Mud Creek), and improved conditions for hunting and fishing. Given the range of “treatments” being applied to the landscape, we can view the region as a site of long-term, large-scale experiments in landscape evolution. The knowledge gained will depend on the quality of the descriptions of the pretreatment conditions, restoration activities, post-restoration monitoring, and the presence of controls for comparison. It is hoped that the results will eventually contribute to sustainable restoration efforts whose cumulative effects will reverse environmental damage. Realizing such benefits, however, will require publication of both successful and failed restoration attempts in a variety of local settings.

Two areas of concern for channel-restoration projects include flood-frequency analysis and excess sediment. The low-gradient valley bottoms of West Tennessee naturally flood more frequently than once per year. If new channel designs are based upon the untested assumption that natural channels typically flood once every 1.5 yr (e.g., TDEC, 2004), the resulting channel will be oversized compared with extant, relatively unmodified streams of West Tennessee. Economic losses will occur if expensively restored channels become occluded by high sediment loads from headwater erosion and upstream canal-bank adjustment (e.g., Simon, 1989a, 1989b), and flow impairment from large wood accumulations and beaver dams. Single-thread river-restoration projects in low-gradient valleys will have a greater chance of success if sited in the sediment shadow of a valley plug.

Challenges remain in local and regional restoration efforts. State-sanctioned stream-mitigation policy (TDEC, 2004), as actualized in the Tennessee Stream Mitigation Program (TSMP, 2007), does not include enhancement or conservation of valley-plug systems or augmentation of self-restoration conditions associated with extant historic meanders. Thus, a number of large-scale, potentially high-impact and low-cost restoration opportunities are receiving little attention. Because remnant historic channels pose opportunities for low-effort, low-risk restoration, there is a need for more detailed channel-evolution models for avulsed canals (e.g., Happ et al., 1940). A practical approach would be to observe how rivers are naturally recovering, and to accelerate those processes using appropriate scales of technology (handsaws, track-hoe, explosive charges, etc.). Policies that encourage the augmentation of natural stream recovery may offer the lowest cost, lowest risk restoration opportunities available, because natural processes can do much of the work and maintenance. The best opportunities will be found where a channel is partially or completely occluded by sediment or woody debris, and assisted avulsion would result in the flow reoccupying historic channels (e.g., Figs. 8 and 9 and Middle Fork Forked Deer River at Law Road). Challenges with this approach include fixing the position of the avulsion channel in cases where upstream migration (e.g., Fig. 10) is undesirable, and sediment and large wood are a threat to the avulsion channel (e.g., Cypress Creek, McNairy County).

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