A cross section of stream channel restoration

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Interest in restoration of ecological, aesthetic, and recreational values to degraded stream channels has grown enormously in recent years, as has interest in developing flood control strategies that retain ecological values and avoid concrete channelization (Evans 1991; NRC 1992; Williams 1990). The term "stream (or river) restoration" is frequently used to encompass all such efforts at ecologically sound river management, even though some of these projects do not actually involve restoration of ecologically degraded channels, but rather attempt to minimize the negative environmental effects of channel relocation or flood management works. Stream "restoration" in the latter sense has also been termed stream "renovation," "reclamation," or "rehabilitation" (Nunnally 1976; Ferguson 1991; Kern 1992). The purpose of this paper is to review a range of stream restoration project goals and activities carried out in North America and Europe, to present two case studies illustrating contrasting goals and techniques, and to demonstrate the need for systematic studies evaluating the success of restoration projects.

Review of restoration goals and activities

Channel stabilization. Channel instability is a particularly common problem in western North America, where streams that were formerly stable, narrow meandering channels, have been converted into wide, shallow, braided channels in response to destabilizing influences such as ill-advised channel works or land use changes upstream, as illustrated on the Blanco River, Colorado (NRC 1992). By virtue of their discharge and channel gradient, these channels may fall near the threshold between braided and meandering proposed by Leopold et al (1964). In these cases, restoration is undertaken to recreate the original channel configurations, often by using bio-engineering techniques. The Carmel River, California, provides an example where dewatering of the alluvial aquifer by water-supply wells killed bank-stabilizing willows and locally lowered the banks' resistance to erosion (Kondolf and Curry 1986). As a result, floods that had passed through many times previously without causing significant erosion (return period 6-8 years) caused locally massive bank erosion. Moreover, the severe bank erosion was confined to reaches in which the water table was lowered by pumping of municipal supply wells. The goal of a restoration project along the Carmel River was reestablishment of stable channel geometry through construction of a bankfull channel of appropriate dimensions and planting riparian vegetation along channel banks and on a reconstructed floodplain (Matthews 1990).

Control of bank erosion. Some stream "restoration" projects do not tackle system-wide instability, but only local bank erosion that threatens structures, agricultural land, or other resources. Bank erosion along the outside of a meander bend and deposition inside the bend on the point bar is a part of natural channel migration. This disturbance regime creates new surfaces on which tree seedlings become established, thus determining patterns of riparian vegetation succession. However, even when the bank erosion results from natural migration, resources threatened by erosion or flooding may create the demand for a bank protection project. The need for such projects is often not carefully analyzed. In many cases, it may be less expensive in the long run (and less environmentally destructive) to move threatened structures out of the path of natural channel migration than to construct bank protection works. Ideally, a river corridor can be reserved to accommodate the natural processes of channel migration and overbank flows (Ferguson 1991).

Bank protection works span a wide range. The goal of many "restoration" projects is to protect banks with the fewest possible environmental impacts, using such approaches as: planting riparian vegetation; use of willow (Salix sp.) spiling (retaining walls constructed of willow stems woven together and from which live willows sprout); willow wattles; post-and wire revetments with willow planting; cabling of dead trees along the eroding bank; and installation of deflectors to direct currents away from the threatened bank (Sotir 1981; Gray and Leiser 1982; Gough 1991).

Harder, more "engineered" bank protection measures include emplacement of gabion baskets (preferably with interstitial soil and willow shoots), riprap, masonry walls, concrete walls, boulder walls. Informal bank protection has utilized materials such as concrete rubble, automobile tires, and automobile bodies. Gabions, riprap, and concrete rubble can be designed to accommodate willows or other riparian plantings in the interstices of the large elements (Henderson 1986). However, hardening an iso-

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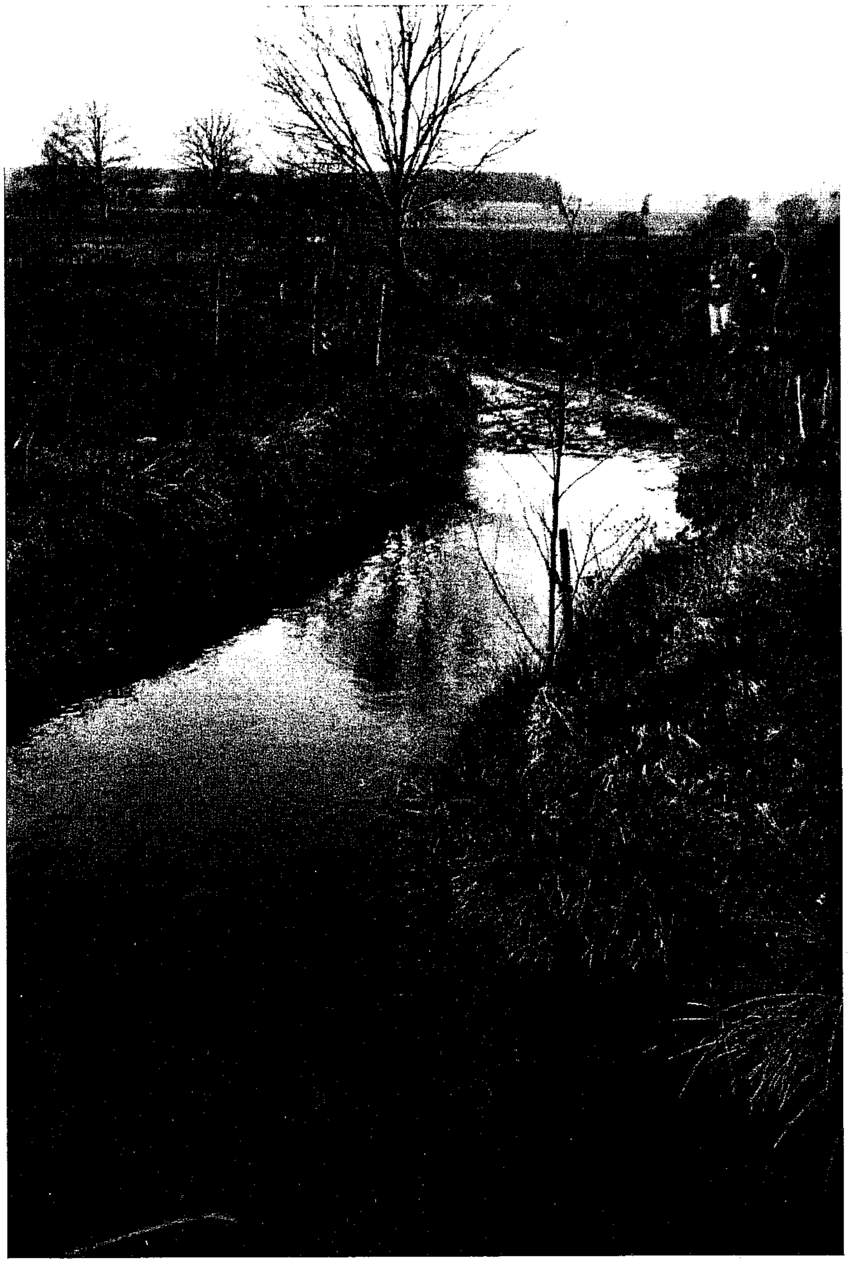

Figure 1. Photograph of the Boyerbach, near Windach, Bavaria, looking downstream to meanders, recreated in this artificially straightened channel

lated stretch of bank inevitably alters local flow conditions. Frequently the current is reflected by the hard surface and redirected against the opposite bank, setting up bank erosion problems upstream or downstream of the protected area. If the bank can be made more resistant without creating a hard surface, it is less likely to reflect currents against the opposite bank and produce instabilities that may propagate downstream.

Techniques that rely on vegetation are particularly vulnerable to washout by floods until enough years have passed for the vegetation to become well established. Thus, a tradeoff can be described between natural attributes (appearance, habitat, minimal impact on the flow field) and reliability. Natural treatments may also require more space. In urban settings, hard engineering treatments are often selected because of the competition for and the high value of land.

Restore natural meanders and bed morphology in a channelized reach. Thus far, restoration of meanders to straightened channels has occurred primarily in Europe, notably Denmark and Germany. The streams of Denmark are nearly all lowland streams, most of which were channelized to improve agricultural drainage, to control flooding, or to maximize land available for development. Widespread concern over the resulting loss of ecological values in Danish streams led in 1982 to national legislation directing that straightened streams be "renatured" wherever possible. As a result, meanders are being recreated on a large scale, accompanied by creation of pools, riffles, and asymmetric cross sections at bends, as well as emplacement of gravels in many channels to recreate more natural bed conditions (Brookes 1987).

Another well known meander restoration project was carried out on the River Wandse, in Hamburg-Rahlstedt, northern Germany (Glitz 1983). However, while meanders were recreated in the formerly straightened reach, pools, riffles, or irregular cross sections at bends were not created to vary the bed morphology (A. Brookes, pers. comm. 1992), so the habitat value of the project may be minimal. In a high-energy system, the river would likely reassert itself and create an irregular bed profile as sediment is redistributed during high flows. However, in a low-energy reach, such channel adjustments will be slow in coming if at all. More successful was the restoration of the Boyerbach near Windach in Bavaria, southwest of Munich. Not only were meanders restored to this straightened channel, but the bed profile and cross section was varied to produce a remarkably natural channel (Figure 1).

Unfortunately, no cross sections have been surveyed to document progressive evolution of the channel form, but field inspection reveals features characteristic of a natural channel: actively accreting point bars, actively eroding outside bends with deep pools, and shallow riffles with clean gravel.

Except for plans to restore meanders on the channelized Kissimmee River in South Florida (NRC 1992), restoration of meanders has yet to occur on a wide scale in North America. In fact, the US Army Corps of Engineers, the Soil Conservation Service, and local flood control agencies continue to propose channelization projects, despite the wealth of information on the frequently disastrous environmental and engineering effects of such schemes (Keller 1976; Brookes 1988; Williams 1990).

Channel relocation. Stream "restoration" in this context refers to incorporating as many environmental values as possible into a relocated, constructed stream channel. Where the stream to be relocated is already channelized, the channel relocation project may provide an opportunity for real environmental enhancement because the new channel can be designed to incorporate greater habitat values over the long run. Where the original channel is natural, the natural dimensions and sinuosity should be recreated as nearly as possible in a new course nearby. If the channel is run in a straightened course to avoid a development, its gradient will be steepened and natural morphology lost.

In the UK, the National Rivers Authority Thames Region now requires that a mirror image of the relocated channel be created opposite the original course so that the channel pattern and length are maintained (A. Brookes, pers. comm. 1992). Highway realignment near Glynneath, Wales, originally called for straightening a reach of the River Neath. An alternative course was suggested by the parish boundaries, which recorded the alignment of a former, centuries-old course of the river (Halcrow 1989).

Flood-control works. Many projects termed "stream restoration" are prompted by the need to modify the channel for flood control. In many of these cases, the "restoration" projects actually involve disruption of the natural channel and riparian corridor, not the restoration of a previously degraded system. These are probably better termed environmentally sensitive flood control works. Most stream restoration work in urban and suburban areas of the United States, United Kingdom, and Germany is financed by flood control projects, although no systematic compilation of such figures has yet been made. However, where the environmental values of the existing channel are degraded, the new flood control channel may effectively restore hydrologic functions and ecological values to a degraded system.

Environmentally sound flood control are more frequently being implemented in lieu of traditional "hard engineering" approaches, which are not only environmentally destructive but commonly technical failures as well (Williams 1990). One option is probably construction of a flood relief (bypass) channel or culvert to accommodate flood flows, leaving the natural channel undisturbed. This relief channel may be dry except during floods (e.g., Walnut Creek, California) or it may have perennial flow (e.g., the River Thames at Maidenhead, UK). Where the structures at risk occupy a limited area of the inundated floodplain, flood walls can be employed to allow floods to overflow the river's banks while protecting floodplain developments. Flood walls may not work in valleys underlain by coarse-grained alluvium because of seepage under the flood walls.

Where alternatives are not possible and the capacity of a natural channel must be increased, the impact on the channel should be minimized. One alternative is to work from one bank only, leaving the natural low-flow channel and the opposite bank's riparian vegetation undisturbed. Another entails construction of multi-stage channels to accommodate flood flows in shelves cut into the terrace or floodplain while retaining a narrower low-flow channel (Purseglove 1989). The 1980 flood control project on the River Roding near Abridge is an example of a two-stage channel, with construction disturbance on one bank only, and with rapid vegetation of the newly constructed floodplain within the two-stage channel (Weeks 1982; Raven 1986).

Enhancement of aquatic and riparian habitat. These projects are usually carried out to increase habitat for preferred or endangered species (typically salmonids or riparian birds), although restoration of habitat for the aquatic invertebrates, macrophytes, and other species may also be considered. The specific projects undertaken vary depending on the species of local concern and the factors perceived to be limiting their populations. For example, in many high-energy streams of western North America (especially those affected by increased erosion resulting from land use in the watershed), salmonid production is often limited by availability of pool habitat. There have been many attempts to create more pools directly by excavation, or indirectly by installing log- or boulder-deflectors along banks to concentrate flow and induce scour, placement of boulders in mid-channel to induce scour downstream, or construction of vertical walls to induce scour along the bank. Another approach is to install weirs to pool water upstream and increase habitat diversity. In addition to projects designed to increase pool habitat, enhancement works are undertaken to provide cover or improve spawning areas (Swales and O'Hara 1980).

Aquatic habitat enhancement by instream channel modification has long been popular, as exemplified by extensive enhancement work in trout streams of Michigan (Tarzwell 1932). Such projects have been undertaken in channels whose natural geometry had been severely disrupted by human activity (Warner and Porter 1960), in newly created or modified channels (Shields 1983), and in relatively natural channels. Such artificial structures have been extensively used in northwestern North America to enhance salmonid habitat, but post-project surveys have shown high failure rates (Frissell and Nawa 1992).

Water quality improvement. By slowing runoff, inducing deposition of suspended sediment, and increasing uptake of nutrients by plants, riparian wetlands and the entire riparian corridor serve to buffer or filter runoff from uplands before it reaches the stream itself. Many projects have been undertaken to restore this function of the natural riparian zone, as well as to reduce direct delivery of sediment from bank erosion to the stream. A number of restoration projects have been undertaken to improve the water quality of runoff into Lake Tahoe (Todd 1989).

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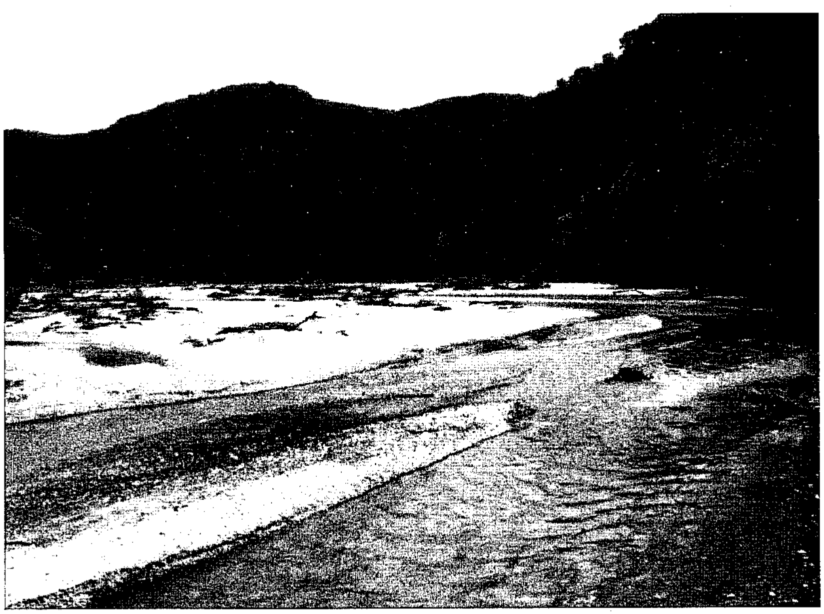

(a) In 1983, showing the wide, unstable, braided channel following extensive bank erosion

(b) In 1992, five years after construction of the restoration project

Figure 2. Photographs of the Carmel River looking upstream from the Schulte Road bridge

Case study: Carmel River

The Carmel River drains a 250 mi^2 (600 km^2) watershed in the rugged Coast Ranges of California, debouching into the Pacific at Carmel, about 100 mi (150 km) south of San Francisco. Upper reaches of the river traverse steep canyons and flow over bedrock, but the lower 15 mi (24 km) flow through an alluvial valley, over a fill of sand and gravel. Rainfall is seasonal, with 90 percent occurring from November to April and runoff displaying similar variability. Under natural conditions, winter and spring floods were followed by gradually declining baseflow, maintained by groundwater discharge from headwater slopes and high alluvial water tables during summer and fall. Since the 1960s, pumping of the shallow aquifer for municipal water supply has locally depressed the alluvial water table, making the river lose water to groundwater (Kondolf et al. 1987). The alluvial water table was locally drawn down over 30 ft (10 m), resulting in massive die-off of willows and other riparian vegetation, destabilization of the banks, and massive erosion during moderate floods (6-8-year return period) beginning in 1978. Near the Schulte Road Bridge, channel width increased from about 80 ft (25 m) to 1,000 (300 m), changing from a single-thread meandering channel with well-vegetated banks to a braided sand-and-gravel channel with eroding banks (Kondolf and Curry 1986).

The Monterey Peninsula Water Management District (MPWMD), a regional agency that regulates the private water purveyor, established a river management program and embarked on a project to restore a single-thread meandering channel (with a riparian corridor) to a 3,200-ft (980-m) long reach upstream of Schulte Road. The goals were to restore channel stability and improve aquatic habitat for anadromous steelhead trout (*Oncorhynchus mykiss*) by narrowing the active channel and restoring bank vegetation. A two-stage channel was created: an active channel with capacity for the 2-year flood, and a floodplain (with capacity in excess of the 100-year flood) on which lines of willows were planted in a herringbone pattern to slow overbank velocities and direct water back into the active channel. The active channel margin was planted with willows for bank protection, reinforced with post-and-wire revetment along the outside bends (Figure 2). Because the low water table problem has not been solved, the willow plantings cannot survive without drip irrigation (Matthews 1990).

To evaluate the success of the Schulte Road project in terms of channel stabilization, cross sections for pre-project and post-project conditions were compared with channel conditions in 1992 after passage of a flood with a return period of approximately 6 years (Figure 3). The low flow channel migrated against the granitic bedrock of the left bank, scouring a pool 10 ft (3 m) below the constructed floodplain surface. This is considered a positive adjustment, as it creates good habitat and effectively recreates the pool described at this site by Steinbeck (1945) in *Cannery Row*. Overall, the 3,200-ft (980-m) long project remained stable in the 6-year flow. Because this project relied upon riparian vegetation for bank stabilization, its success may be largely due to the absence of large floods in the years immediately following plantings. This allowed willows to establish themselves and develop a dense root mat to resist flood scour. If floods had occurred in the first two years following planting, it is likely that the willow seedlings would have been scoured. In a subsequent, larger flood in 1993, this project was undamaged, but two nearby restoration projects constructed in the fall of 1992 failed, probably largely because vegetation had not yet become established (Graham Matthews, personal communication 1993).

Case study: Wraysbury River

The Wraysbury River, one of numerous channels of the Lower Colne River system, flows along the western margin of Heathrow Airport, near Staines, UK. A 1,600-ft (0.5-km) reach near the Skyway 14 Trading Estate was vulnerable to flooding, and the dense development of motorway and industrial/commercial uses around the stream precluded construction of a continuous flood relief channel. As a result, the capacity of the channel itself had to be increased. The traditional engineering approach to this problem is illustrated 0.5 mi (1 km) upstream, where the channel had been relocated and straightened to accommodate construction of the M-25 orbital motorway, widened and deepened to accommodate floods (Figure 4). The channel of the Wraysbury River near the trading estate, although artificially constructed decades ago, had developed a dense riparian cover and a diverse aquatic habitat. The project described here, designed and built by the National Rivers Authority Thames Region in 1990 as part of the Lower Colne Flood Alleviation Scheme (NRA 1990; Gardiner 1988) sought to retain as many of these natural values as possible.

The basic approach was to leave the existing channel bed undisturbed, adding capacity by pulling back the left bank. Where large riparian trees were present along the left bank, they were retained, and the needed capacity was added by excavating a secondary channel, leaving the trees on an island in the center of the channel (Figures 5 and 6). Aquatic habitat diversity was increased by varying bed elevations, excavating deep pools and importing gravel for riffles. Blocks of limestone were emplaced as angled deflectors to produce zones of higher velocity as well as sheltered, backwater sites. Banks were stabilized with willow spiling where possible; limestone blocks were used in places where adjacent vertical banks required support.

One approach to evaluating the success of this project is to compare channel geometry of the project reach with that of the traditional trapezoidal channel flanking the M-25 motorway upstream. The project reach is characterized by a variety of cross sectional forms, from deep pools to shallow riffles and split channels around islands. The complexity of channel form (and resultant aquatic habitat) can be indicated by the coefficient of variation (COV) of depth from individual measurements made in August 1992 across eight cross sections in the project reach (n = 111) and eight cross sections in the trapezoidal reach (n = 68). In the project reach, water depth averaged 0.49 ft (0.15 m), with standard deviation of 0.43 ft (0.13 m), yielding a COV of 0.87. In the trapezoidal reach, depth averaged 1.5 ft (0.46 m), with a standard deviation of 0.39 ft (0.12 m), yielding a COV of 0.26. The COV of depth holds promise as one useful index of relative complexity of aquatic habitat (Jungwirth et al. 1993), but it should be accompanied by other geomorphic and biological measures for a complete assessment of stream channel condition.

Contrast between European and North American projects

Many river restoration projects in North America emphasize channel stabilization through simple techniques such as cabling red cedar trees (*Juniperus virginiana*) to eroding banks to protect banks and induce scour of aggraded channels (Gough 1991), or more ambitious resculpting of over-widened, braided channels into single thread channels with improved stability and aquatic habitat (Matthews 1990; NRC 1992). English and German pro-

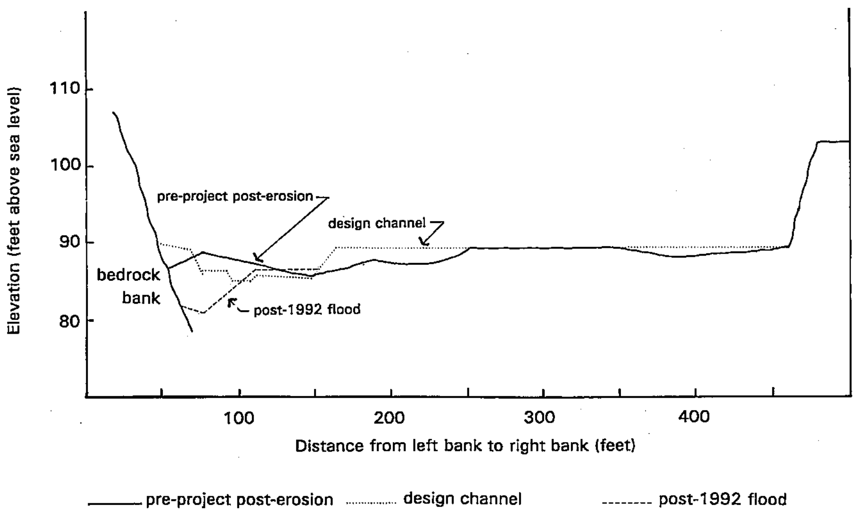

Figure 3. Cross sections of the Carmel River approximately 700 ft (200 m) upstream of Schulte Road bridge
(Note: This figure shows pre-project conditions after severe bank erosion of 1980-1983), as-built project conditions in 1987, and channel conditions following the 1992 runoff season (return period of peak flow 6 years). Looking downstream.
Cross sections from W.V.G. Matthews

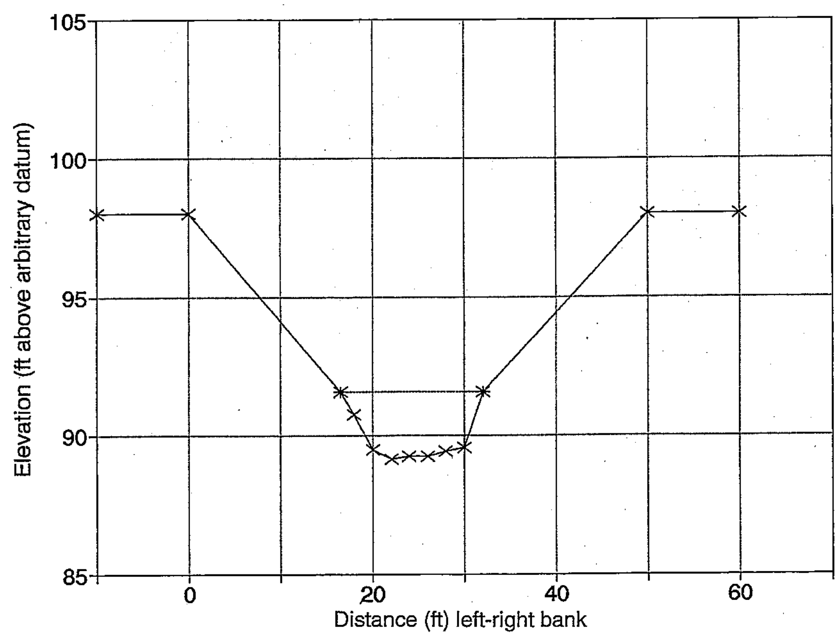

Figure 4. Cross section of the Wraysbury River in a traditional straightened, trapezoidal channel adjacent to the M-25 motorway
(Note: Orientation: looking downstream) Survey August 1992 by the author

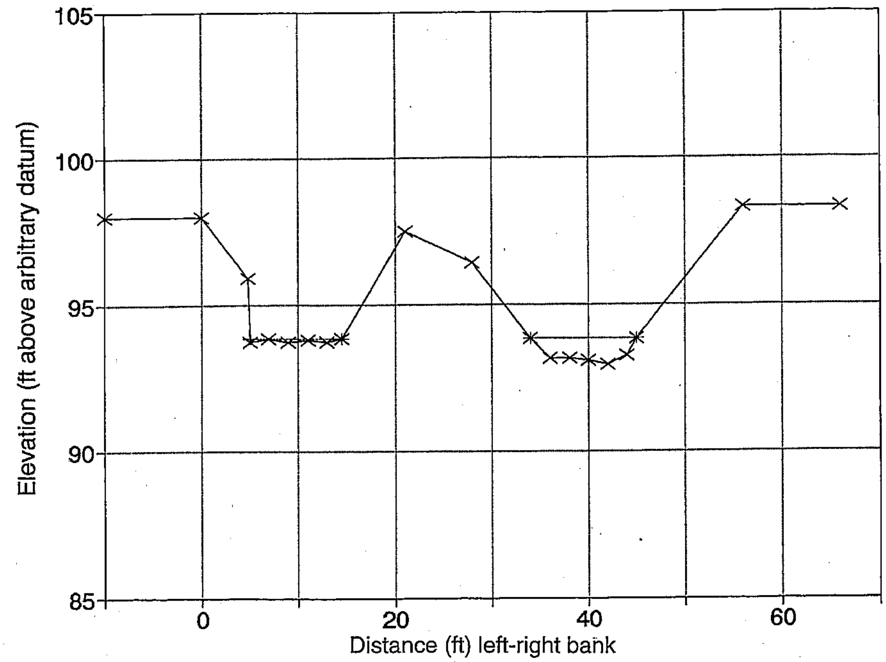

Figure 5. Cross section of the Wraysbury River in the restoration project reach adjacent to the Skyway-14 Industrial Estate

(Note: The right channel is the pre-project channel, which was left undisturbed to retain well-developed riparian trees along its left bank. Additional channel capacity was obtained by excavation of a flood relief channel to the left, leaving the vegetation on a mid-channel island. Orientation: looking downstream.) Survey August 1992 by the author

jects tend to emphasize habitat creation with increasing reluctance to constrain channel migration. The philosophy underlying present efforts at environmental enhancement of Bavarian rivers is to leave natural processes alone wherever possible, allowing rivers to freely migrate and erode banks (Walter Binder, Bavarian Interior Ministry, personal communication, 1992). The rivers that flow from the Alps have been controlled, resulting in a loss of braided channels with open unvegetated gravel bar habitat to which some species are adapted. Thus, some braided channels that North American restoration projects seek to convert into meandering channels might be highly prized in Europe for their wildness. On both continents, there is increasing use of vegetation for bank stabilization, avoidance of traditional trapezoidal flood control channels, and incorporation of environmental enhancement in channel projects (Henderson 1966; Binder et al. 1983).

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Figure 6. View of the restoration project reach on the Wraysbury River at the Skyway-14 Industrial Estate, looking upstream to the island shown in Figure 5

Post-project evaluation

Despite the many stream restoration projects carried out to date, we are severely limited in what we can learn from this collective experience because few post-project evaluation results have been reported. Moreover, it is difficult to conduct post-project evaluation for completed projects because baseline information is rarely available (Kondolf and Micheli 1995). It is striking that vast sums are spent on project construction but little on collection of baseline data and follow-on studies to demonstrate whether the projects are worthwhile. Holmes (personal communication 1992) surveyed 100 river enhancement projects undertaken by the U.K. National Rivers Authority (and its predecessors, the regional water authorities) through 1992. He found that only five had been subject of post-project evaluation reports and of these only two were evaluated from a multi-disciplinary perspective. The situation is probably worse in North America, where concern for post-project evaluation has yet to produce a comprehensive survey of post-project evaluation of restoration projects. Some funds for enhancement projects in California allow expenditures for construction only, none for background studies or post-project monitoring (California Department of Fish and Game 1993). In the case studies presented here, some measure of success was gleaned from comparison of cross sections for pre- and post-project conditions or contrasting environmentally enhanced with traditional (trapezoidal) channel designs. More such studies will be needed if we are to improve our collective base of knowledge about effectiveness of stream restoration approaches. Post-project evaluation requires baseline data of comparable quality to the data collected post-project. This is rarely collected now, but should be incorporated into new projects. Depending upon the project purpose, the following can be monitored: channel capacity and channel stability, aquatic and riparian habitat, fish and wildlife populations, water quality, visual quality, and recreational use. Ideally, specific criteria for success should be established, and the post-project monitoring should be incorporated into the initial project planning (Kondolf and Micheli 1995).

Summary and conclusion

The term "stream restoration" is used to encompass a wide range of actions, reflecting diverse hydrologic conditions and project objectives. Projects involving environmentally sensitive flood control or channel relocation are commonly included under the rubric of "stream restoration," even when they involve disruption of an existing natural channel with ecological values intact. In such cases, the benefits of these approaches can be evaluated by contrasting the resulting channels with traditional alternatives. Historical studies can document previous channel conditions to provide a basis for understanding the underlying cause of channel instability and guidance on appropriate configurations for the restored channel (Kondolf and Micheli 1995).

Given the wide range of restoration projects, it is important the goals of a particular project be clearly articulated prior to its design. The techniques chosen must reflect not only those goals, but also the accumulated knowledge of success and failure in previous application of these techniques. This accumulated knowledge can come only from systematic studies of restoration projects (in which the distinctive features of each setting and project are explicitly recognized) and the wide dissemination of those results.

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