AQUATIC HABITAT ENHANCEMENTS FOR MAD RIVER AND BEAVER POND BROOK IN CONJUNCTION WITH THE RECONSTRUCTION OF I-84, WATERBURY, CONNECTICUT

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Abstract: In conjunction with proposed highway improvements scheduled for I-84 in Waterbury, Connecticut, reaches of Mad River and Beaver Pond Brook will be relocated. A team of consulting engineers and ecological scientists provided analysis and design services for habitat enhancements for the affected river resources. The existing watercourses affected by the highway project have been highly altered by previous urban development activity, which has degraded the habitat function of these streams. Therefore, the design focused on creation of a naturalized channel for each affected watercourse reach, with habitat features that replicate and, if possible, improve upon the functions observed in the current watercourses.

Design objectives included consideration of channel conveyance capacity and stability, channel improvements compatible with highway alignment and structural design, and provision of structural habitat features and other in-stream and riparian enhancements. The design project involved the application of "natural channel design" techniques and traditional hydraulic engineering and structural design approaches. The design addressed critical elements, such as channel reaches, that no longer have functional floodplains, potential scour at bridge structures, and removal of obstructions to fish passage at existing structures. One of the major features influencing design was the presence of a remnant dam spillway.

The design process involved analysis of geo-morphological characteristics and habitat features of existing river reaches. Relocated river segments incorporate appropriate pool-riffle sequence, substrate conditions, and other habitat structural elements. Riprap grade control structures were integrated into the habitat enhancements. Design also provided for introduction of riparian vegetation; culvert replacements and extensions incorporating fish passage features; and replacement of an existing inadequate fish-way structure previously constructed in a partially breached dam.

The design project demonstrated that natural channel design techniques, wetland and aquatic vegetation restoration techniques, and more traditional hydraulic and structural channel design engineering practices can be integrated to achieve a design conducive to the replication and enhancement of fisheries and riparian habitat functions in altered urban stream channels. The design process and design concepts developed in this project are adaptable to similar transportation improvement projects that involve impacts to existing stream and river resources.

Introduction

The Connecticut Department of Transportation (ConnDOT) developed the design of major highway improvements proposed for I-84 in Waterbury, Connecticut. The project design required the relocation of approximately 535 meters of Mad River (62.5-square-kilometer watershed) and 890 meters of Beaver Pond Brook (14.6-square-kilometer watershed) within the highway corridor. To address the environmental effects of this activity, ConnDOT retained a team of consulting engineers and ecological scientists to provide analysis and design services for the provision of habitat enhancements for the affected river resources. The Federal Highway Administration and the Connecticut Department of Transportation funded the project.

The design team needed to address the reconstruction of an existing highway, with constraints imposed by the existing urbanized location, current standards for highway design, and available space for highway realignment. In addition, the existing watercourses affected by the highway project had been highly altered by urban development activity, which had degraded the habitat function of these streams. Therefore, the design team also needed to address the development of relocated channels for selected reaches of each affected watercourse, incorporating habitat features that replicate and, if possible, improve upon the functions observed in the existing watercourses.

Mad River and Beaver Pond Brook are both typical urban watercourses that have been significantly altered by human activity. Within the limits of the project area, floodplains of both streams have been filled or developed, leaving only a few remnant floodplain areas. Most of Mad River appears to have been either relocated or channelized in the past, and various run-of-river dam configurations have impounded the river. The partial breach of a dam on this river occurred in 1998, resulting in instability of the river within the former impoundment. Transport of sediment as a result of this partial dam removal has also resulted in downstream impacts.

Beaver Pond Brook was extensively channelized in the 1960's in conjunction with the original construction of I-84. For most of its length, the brook is located within a riprap-lined channel. In one location, the brook retains a limited area of functional floodplain with a forested wetland plant community.

Both watercourses are subject to the hydrology associated with a highly urbanized watershed, with extremely low base flows, and with high-energy flood flows largely confined to the primary channels. In general, the Mad River and Beaver Pond Brook lack the productive and diverse habitats found in less intensively developed watersheds.

The project objective was to develop the design for river relocations that provided for:

- Conveyance capacity for a range of flow conditions, including low flows, seasonal flows during fish migration periods, and flood flows
- Channel improvements compatible with highway alignment, structural, and hydraulic design standards
- Replication of habitat functions of the existing river segments within the relocated channel segments

This paper describes the design development process for achieving a naturalized channel design within the constraints of the highly urbanized setting of the existing watercourses.

Overview of the Design Process

The design project involved the application of "natural channel design" techniques and traditional hydraulic engineering and structural design approaches. The design effort had to address critical elements including the following:

- Design constraints imposed by the location of previous structures, adjacent land uses, and the maintenance of traffic during construction
- Replacement of river channel reaches that are subject to the hydrologic regime resulting from extensive historic development of the watershed
- Channel capacity design that accounts for the lack of adjacent floodplain because of past development encroachment
- Channel stability design, particularly in the vicinity of proposed bridge structures, where potential channel scour was a major design concern
- Removal of obstructions to fish passage at existing structures (including a remnant dam spillway), and prevention of obstruction impacts at new structures, including several new or reconstructed culverts
- Development of a channel structure that would be supportive of fisheries habitat, within a channel design "template" that addresses the other critical elements listed above

The design process resulted in a highway alignment that accounted for highway safety, capacity, and access/egress requirements. In conjunction with the realignment design, basic layouts of the channel alignments were developed for Mad River and Beaver Pond Brook, a major tributary within the project area. The channel alignments were developed on the premise of minimizing culvert length and the length of channel beneath bridges. In fact, a driving factor in relocating the channels was to avoid extensive placement of channel within culverts, which would have been required with alternative designs. Channel cross sections were also developed based on hydraulic modeling using HEC-RAS.

Refinements for this basic "template" for channel design were then developed based on a study of the existing river and brook conditions. The design used this information to apply natural channel design techniques and other methods for enhancing fisheries habitat, drawn from available literature (e.g., Rosgen 1996; Federal Interagency Stream Restoration Working Group, October 1998; MDE 2000; and others).

The design process included the following steps:

- Confirmation of the basic channel alignment and cross-section based on data observed for existing reaches of Mad River and Beaver Pond Brook
- Development of a thalweg (thread of stream) pattern associated with observations of bankfull channel width and depth, and prediction of a pool/riffle sequence based on this thalweg pattern
- Design placement of streambed structures to reinforce pool/riffle sequence and provide habitat structure
- Selection of streambed materials based on materials encountered in the existing river system
- Development of a fish passage structure to overcome the obstruction posed by the partially breached dam
- Design of treatments for culverts to enhance fish movement through the structures
- Design of plantings on the channel embankments, marginal floodplain areas, and near-bank upland areas, to promote development of a vegetated riparian corridor
- Provision of other features to enhance habitat where feasible, including provision of bank cover structure in selected locations, and development of a remnant river channel into an “oxbow wetland”

These design features are discussed further below.

Development of Habitat Structure

To obtain data to inform the design of the relocated channels, the design team conducted an analysis of existing reaches of the river and brook relative to geo-morphological characteristics and habitat features. The reference models for channel reconstruction comprised selected sections of Mad River and Beaver Pond Brook within or adjacent to the area of reconstruction. The use of the local river and stream reaches was warranted based on the need to select channel segments that would be subject to a similar hydrologic regime as the proposed relocated channels. The use of a relatively pristine stream channel to develop data to apply to the design of a channel in a highly urbanized setting was considered inappropriate. Such an approach would not reflect the hydrologic conditions that would affect the continuing function of a reconstructed channel in an urban environment.

However, using an existing urban-influenced stream to develop basic data on bankfull width, bankfull depth, and other parameters useful for natural channel design can be challenging. Ongoing urban development and redevelopment in a watershed can result in changes in hydrology and sediment load and gradation, which can in turn result in changes in stream morphology. Urban streams can be in the process of adjustment in response to such changes in the watershed. As a result, urban streams can be unstable, and bankfull cross-section may be in the process of changing. In the case of the Mad River, the partial removal of a dam spillway occurred in the late 1990’s. That activity drained an impoundment that extended into the project area. It also introduced instability into the stream segment proposed for relocation, particularly within the area formerly occupied by the impoundment. The action also may have affected continued sediment conveyance and deposition upstream and downstream of the former impoundment. The characterization of the existing river’s bankfull cross-section needed to be performed recognizing that the river had been affected by this dam removal activity. This constraint was addressed by selecting relatively undisturbed segments of stream for analysis of bankfull geometry, and comparing the data obtained with “regional curves” relating bankfull depth, width, and discharge to watershed area (Dunne and Leopold 1978).

Once representative data for bankfull depth and width were obtained from the local “reference reaches” and compared to literature values, the initial channel alignments and cross-sections were compared to these data, and found to be in reasonable agreement. Therefore, the basic alignment and cross-sections, established by the initial engineering hydraulic analyses, were retained in the design.

The bankfull width was used to develop an anticipated thalweg pattern for the proposed channel alignment. Both Mad River and Beaver Pond Brook have a boulder/cobble structure and moderate slopes. This course bed material in a natural stream does not necessarily show a clear sinuous thalweg (the “thread of stream” that follows the deepest part of the channel), as would be evident in streams with more fine-grained bed material. However, field observation does reveal such a thalweg in the existing streams, although it tends to be irregular in shape. A hypothetical thalweg pattern was projected onto the proposed channel alignment, based on the natural tendency of streams to develop a meander wavelength equal to about 10 to 14 times the bankfull channel width (Rosgen 1996).

This thalweg pattern was used to predict approximate locations of pools and riffles that would be anticipated for a river of the identified bankfull geometry. These locations governed the placement of selected structures for reinforcing the pool/riffle development of the stream. Pool/riffle structure comprises a series of relatively quiescent pools, separated by fast flowing stretches of relatively shallow flow ("riffles"). Pool/riffle habitat may be enhanced by several methods, including the use of "wing deflectors," "vortex rock weirs," "cross vanes," and "j-hooks." Random boulder placement can also be used to add additional "micro-structure" to the resulting channel bed-form. These structures are further described below.

Wing deflectors: These structures consist of low profile V-shaped jetties fabricated of large boulders with cobble in-fill, installed adjacent to the embankment of the stream. Each deflector is anchored into the embankment, with the upstream edge of the deflector forming an approximate 30-degree angle with the stream bank. These deflectors direct the river current at low and normal flows. Higher flows overtop the structures. The wing deflectors deepen and narrow the channel thalweg. This helps protect stream banks from erosion, and enhance benthic and riparian habitat conditions (Wesche, 1985). The immediate downstream side of the deflector is subject to scour, and bed material tends to re-deposit further downstream of this scour hole. The deflector structure, the resulting downstream deposition area, and the associated scour pools contribute to the formation of the alternating pool-riffle habitat that is the design objective.

For this project, one benefit of a wing deflector is that it can help the river recover a narrower base-flow channel geometry in a section of reconstructed channel that had been developed significantly wider than the natural bankfull width. This benefit was observed in a downstream section of Mad River that had been reconstructed in a previous project in the late 1990's. Therefore, a wing deflector was designed for the overly-wide armored channel that was installed immediately upstream of the remnant dam spillway when the dam was breached. The structure is intended to reinforce the river's current tendency to form a primary channel along one side of the riprap-lined channel section. The wing deflector was sized and located according to procedures cited by Wesche (1985) and Ontario MNR (undated).

Vortex Rock Weirs: Vortex rock weirs comprise very low-head, run-of-stream drop structures made of boulders set into the riverbed (MDE 2000; Rosgen 1996). The series of boulders is installed across the width of the normal flow channel. Gaps are provided between the individual stones. The boulders are placed in a crescent pattern, with the convex side of the crescent pointing upstream. This "gap-toothed" structure restricts low and normal stream flows, causing a slight ponding upstream of the structure, and scour downstream of the structure. Eroded bed material naturally re-deposits on the channel bottom downstream of this scour. The result is an alternating pool/riffle habitat structure.

Typical placement is at the head and tail ends of pools, at the head and tail ends of riffles, or at a two- to three- stream-width spacing for a step-pool effect. Gaps between vortex rocks typically equal one-quarter to one-half rock width. The rocks are sized for stability under anticipated flow conditions (based on a "pick-up" velocity, incipient motion analysis, or riprap selection procedure).

Cross Vanes: Cross vanes (MDE 2000) comprise weir structures similar to vortex rock weirs, except the rocks forming the top of the weir are butted together rather than laid with gaps. The structure will act more as a check dam, with more ponding upstream of the structure than with the vortex weir. Cross vane placement is similar to the vortex rock weir, for development of desired pool/riffle sequence. These vanes can also be used in a close-spaced sequence (about one channel-width from weir crest to weir crest) to accommodate a drop in grade, with an overall drop less than 0.6 meters (2 feet), which makes them useful for preventing down-cutting just downstream of a culvert.

J-hook Vanes: These vanes are used to direct normal flows away from stream banks (providing erosion protection), promote development of scour pools and associated downstream deposition (pool/riffle structure), and to initiate/direct thalweg meander pattern (MDE 2000). J-hook vanes consist of single-arm structures partially embedded in the streambed to promote development of scour pools. Each vane tip has a "J" configuration, with the convex end pointing upstream. Vane length for J-hooks may be up to 60 percent of channel width. The top layer of rocks at the "J" tip is set with gaps one-third to one-half rock diameter.

For meander development, these vanes are placed on alternate sides of the channel, with the space between vanes along the stream equal to 5 to 7 times the bankfull channel width. For habitat development, spacing can be equal to one or more channel widths, depending on pool spacing desired.

Random Boulder Placement: Boulders are placed singly or in clusters in random locations within the reconstructed channel. The boulders provide in-stream habitat cover, including feeding lies, and resting areas for fish. Boulders break up uniform currents, dislodging fine sediments and thus enhancing habitat for benthic organisms (Ontario MNR undated). Boulders were sized for stability under anticipated flow conditions based on "pick-up" velocity or incipient motion analysis, and compared with riprap sizing analyses to develop a conservative design.

The placement of the rock vanes and weirs described above was coordinated not only with the desired pool-riffle sequence, but also with the placement of grade control devices designed to control scour in the vicinity of proposed bridge abutments. The project employs riprap grade control structures based on Swiss research (Whittaker and Jäggi 1986; ASCE Grade Control Task Committee 1998). The structures comprise a thickened layer of rounded stone riprap designed to prevent the upstream migration of a channel head-cut, should such a scour feature develop. When the knick-point of a head-cutting channel reaches the downstream edge of this structure, the additional depth of material inhibits further upstream migration of the cut, and riprap from the leading edge of the structure tends to "self-launch" into the scour hole and thus armor the resulting pool bottom.

To complete the "structural" treatment of the relocated channel segments, the design provides for a substrate of granular material, cobbles, stones, and boulders. Stone size for this bed material was determined based on observations of boulder and cobble sizes in relatively stable sections of Mad River and Beaver Pond Brook. The material size was also confirmed by comparison with stone sizes based on riprap sizing procedures for flows comparable to bankfull discharge for the subject streams. The design specified rounded stone material, similar in composition to the in-situ material.

Fish Passage Considerations

To provide for fish passage at the partially breached dam located on Mad River, the design team proposed installation of a rock ramp fishway immediately downstream of the remnant spillway. The design provides for the top of the remaining spillway structure to be lowered for part of its width. The modified spillway and the rock ramp provide a waterway width at bankfull discharge compatible with the bankfull width of the relocated river.

The rock ramp comprises a series of concave boulder weirs, with the apex of each concave arch pointing upstream. The space between these weirs is back-filled with rounded stone riprap placed to simulate a natural streambed. The riprap material includes sufficient fine materials to fill void spaces in the stone, to minimize subsurface flows. The overall slope of the ramp is approximately 26:1 (horizontal:vertical). The structure functions essentially as a steep set of rapids in the profile of the reconstructed channel. It is shaped to provide sufficient depth for fish passage at a variety of flow levels, and the natural bed material and weirs provide a variety of flow conditions that is anticipated to permit fish to negotiate the structure. This type of structure requires little maintenance compared to alternative fishway designs, and is not subject to clogging by natural and cultural debris found in the existing river system. The design of this structure is intended to accommodate blueback herring, an anadromous fish species formerly found in the Mad River, and was based on a compilation of material obtained through the Northeast Field Office of American Rivers and the Minnesota Department of Natural Resources.

Required culverts within the project area were also designed to facilitate fish movement. Design measures included provision of baffles within the concrete box culverts, to act as internal roughness elements for energy dissipation, and to provide for fish passage. In addition, variations on cross vanes, vortex weirs, and rock ramp structures were included in the channel sections downstream of the culverts, to control water levels at the outlets of the culverts and help prevent down-cutting of the channel at these locations. This measure was incorporated to prevent the development of "perched" culverts. This condition occurs where scour and channel degradation downstream of the culvert result in a lowering of the outlet pool to an elevation below the culvert invert, making the culvert inaccessible to aquatic organisms moving upstream.

Stream Bank Vegetation and Other Riparian Enhancements

Riparian vegetation provides habitat cover for fisheries and other wildlife, moderates stream temperatures, serves as a food source, and helps stabilize embankments (Welsch 1992). Therefore, to enhance fisheries habitat, the project design included plantings of channel embankments above bankfull depth for both watercourses. In areas where a floodplain margin could be provided within the constraints of the site, floodplain plantings were also designated. At one location along Mad River, the design provided for a section of abandoned river channel to be developed as a remnant oxbow with a variety of wetland plantings.

The planting design included a selection of native plants, including species observed in the vicinity of the project, tolerant of the conditions prevalent in the watercourse. Because of the high energy flows anticipated, especially within confined channel reaches with limited or no adjacent floodplain, some plantings could be lost during flood events. In these areas, selected plants included shrub and herbaceous species that can self-propagate from stem and root fragments left by a flood event. Outside the flood-way, native shrubs and trees were selected for planting along the upper edge of the river embankment to provide shade and riparian habitat. The embankment plantings were designed for incorporation into voids in the riprap lining of the reconstructed watercourses. The design team has observed that riprap-lined stream banks tend to develop vegetative growth over time even if not planted. However, intensive plantings in connection with the construction promotes establishment of desirable plant species, helping to pre-empt colonization by non-native invasive species.

On a reach of the relocated Beaver Pond Brook that will retain a significant flood plain, the banks of the new channel will include measures to provide bank cover structure. These measures include the following:

> *LUNKERS Structures:* These bank cover structures provide an undercut bank effect, providing hiding cover for fish. The structure is typically constructed with planking or logs, to provide an open-sided box that is buried in the stream bank, with the interior accessible to aquatic organisms (Ontario Stream Restoration Web site). The armored or re-vegetated bank surface extends over the top. Typical installation is along outside bends or along straight reaches in conjunction with deflectors, so that the structure will have an adequate water depth beneath the overhang.
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> *Root Wad Revetment:* Root wads can enhance fisheries habitat by promoting scour pools and providing overhead cover, shade, insect habitat, and a source of organic detritus. Placement of root wads is generally similar to the placement of LUNKERS. The revetment consists of lengths of tree trunk with the root wad intact, placed on a foundation of logs and anchored with boulders. The riprap or re-vegetated bank is integrated with this structure, and coordinated with planting design, to introduce stabilizing vegetation into the bank above the root wad mass. Maryland's Waterway Construction Guidelines provides information for root wad revetment design (MDE 2000).

Conclusion

This project illustrates that natural channel design techniques, wetland and aquatic vegetation restoration techniques, and more traditional hydraulic and structural channel design engineering practices can be integrated to achieve a design conducive to the replication and enhancement of fisheries and riparian habitat functions in altered urban stream channels. Such a design effort must address constraints imposed by the urban setting within which such projects occur and the natural geologic and hydraulic processes that will continue to affect the behavior of the reconstructed channels, as well as the engineering requirements and standards that apply to highway design.

A number of riverine enhancement measures were adapted to this project, within the framework of a safe and functional highway design. The design approach provided for in-stream structural improvements to promote the development of biological habitat within the reconstructed channel, based on geo-morphological analysis. The design proposed augmentation of riparian vegetation along the channel, including riprap plantings, replicated floodplain plantings, and oxbow wetland development. In addition, the design included measures to facilitate the passage of fish and other wildlife along the river, including resolution of the obstruction posed by an abandoned and partially removed spillway structure.

It is anticipated that the design process and design concepts developed in this project will be adaptable to similar transportation improvement projects that involve impacts to existing stream and river resources.

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Mr. Nyman has designed habitat enhancement measures for the reconstruction of the Mad River at the Brass Mill Center, a regional retail center in Waterbury, CT, and the development of shoreline stabilization and floodplain stormwater enhancement measures for the Still River in Danbury, CT. He has also participated in numerous wetland and water resource restoration and enhancement projects in New England, as well as site development projects in unique, sensitive environmental settings.

He is the principal author of the “Hydrology Handbook for Conservation Commissioners,” prepared for the Massachusetts Department of Environmental Protection. In addition, he has served on the Massachusetts DEP Stormwater Policy Advisory Committee, as well as its Stormwater Technical Advisory Committee. He has assisted the Massachusetts Highway Department with the development of that agency’s Stormwater Handbook, and the agency’s Stormwater Management Plan for compliance with EPA NPDES Phase II permitting requirements. He has also authored stormwater management guidance documents for state agencies in Connecticut and Maine.

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